Simulation of water-energy fluxes through small-scale reservoir systems under limited data availability

Konstantinos Papoulakos, Giorgos Polliakis, Yiannis Moustakis, Apostolis Markopoulou, Thanio Iliopoulou, Panayiotis Dimitriadis, Demetris Koutsoyiannis, and Andreas Efstratiadis

1. Abstract
Small islands are regarded as promising areas for developing hybrid water-energy systems that combine multiple sources of renewable energy with pumped-storage facilities. Essential element of such systems is the water storage component (reservoir), which implements both flow and energy regulations. Apparently, the representation of the overall water-energy management problem requires the simulation of the operation of the reservoir system, which in turn requires a faithful estimation of water inflows and demands of water and energy. Yet, in small-scale reservoir systems, this task is far from straightforward, since both the availability and accuracy of associated information is generally very poor. In contrast to large-scale reservoir systems, for which it is quite easy to find systematic, and reliable hydrological data, in the case of small systems such data may be minor or even totally missing. The stochastic approach is the unique means to account for input data uncertainties within the combined water-energy accounting management problem. Using as example the Lixiá reservoir, which is the pumped storage component of the small Aegean island of Astypálaia, Greece, we provide a study of the daily operation comprising: (a) a stochastic model for generating synthetic rainfall and temperature time series; (b) a stochastic rainfall-runoff model, whose parameters cannot be inferred through calibration and, thus, are represented as correlated random variables; (c) a stochastic model for estimating water supply and irrigation demands, based on simulated temperature and soil moisture, and (d) a daily operation model of the reservoir system, providing stochastic forecasts of water and energy outflows.

2. Study area and data
Astypálaia (Aristoteleion) is a Greek island with 1334 residents (2011 census), that belongs to the Dodecanese complex (total area 97 km²). Lixiá reservoir is element of a hypothetical hybrid renewable energy system across the island, aiming at ensuring full autonomy against the estimated electricity needs. Today, the reservoir fulfills domestic, touristic and agricultural ware uses; estimated annual demands are 210,000 m³ for water supply and 230,000 m³ for irrigation.

3. Representation of process uncertainty through stochastic simulation of key meteorological drivers
- Historical hydroeteorological data: daily time series of rainfall and mean temperature from June 2009 to February 2017.
- Significant uncertainty, due to inherent variability and limited length of raw data
- Generation of daily synthetic data (correlated for a 100 year simulation period through Casta model (Efstratiadis et al., 2014).
- The model preserves the essential statistical characteristics (marginal and joint distributions) of historical data at three time scales (annual, monthly, daily), as well as the long-term persistence (Koutsoyiannis & Koutsias, 2013).

4. Outline of water-energy simulation procedure: data, models, parameters, processes
- Monte Carlo model for parameter generation
- Stochastic hydrological model for potential evapotranspiration (ET)
- Soil tank capacity
- Water demand for domestic and touristic use
- Water demand for irrigation
- Percolation to lower soil zones, which is finally conducted to the sea.
- Runoff model (>2100 runs), thus providing daily outputs for 100 year simulation.

5. Monte Carlo approach for handling parameter uncertainty within runoff modelling
- Parsimonious modelling structure, using two daily input time series (rainfall, PET) and three parameters.
- Storage components, by means of conceptual tanks:
  - Interception capacity, C, representing the maximum runoff capacity for temporary rainfall deficiencies in each day;
  - Soil tank of finite capacity, accounting for soil moisture storage fluctuations within the simulation period
- Model outputs:
  - Actual evapotranspiration (ET), comprising direct and soil evapotranspiration;
  - Runoff, comprising overland and saturated flow;
  - Percolation to lower soil zones, which is finally conducted to the sea.
- Model parameters:
  - Interception capacity, C, representing a lower rainfall threshold for runoff generation;
  - Soil capacity, K, representing the maximum soil moisture that can be retained in the unsaturated zone;
  - Recession rate for percolation, α, representing the percentage of soil moisture that moves to the lower zone.
- PET is estimated on the basis of mean daily temperature, through a parametric radiation-based approach, fitted to historical Perman-Monteith data from neighboring stations (Tegou et al., 2013)
- Due to lack of observed runoff the model is subject to major uncertainty, expressed in terms of a priori distributions of parameters; for simplicity, C, K and α are considered uniformly distributed within “reasonable” feasible ranges.
- To reduce uncertainty, we take advantage of our evidence about the hydrological regime of Lixiá catchment (Koutsoyiannis, 2011), thus accepting any parameter set ensuring mean annual percolation and runoff ratios between 10 and 20%.
- By employing Monte Carlo sampling we detected 2300 acceptable parameter sets out of 300,000 feasible sets, independently generated from uniform distributions, thus providing a posteriori quantification of uncertainty and insight to nonlinear dependencies between parameters.
- For each behavioral combination of parameters, we ran the model in stochastic mode, thus producing 2300 synthetic runoff scenarios to the reservoir simulation model.

6. Reservoir management in stochastic setting
- Problem statement: Demand of water supply and irrigation demands;
- Preservation of backup storage for employing energy regulations.
- Model inputs and associated uncertainties:
  - Catchment runoff, provided by the stochastic hydrological model (with uncertain parameters), driven by synthetic rainfall and temperature;
  - Rainfall over the lake area, synthetically generated;
  - Evaporation losses, estimated on the basis of synthetic temperature;
  - Water demand for domestic and touristic use, estimated on the basis of population data and per capita consumptions that depend on temperature;
  - Water demand for irrigation, estimated on the basis of crop data and evapotranspiration deficits (output of hydrological model).
- Monte Carlo approach, accounting for all behavioral parameter sets of rainfall-runoff model (~1200 runs), thus providing daily outputs for 100 year simulation.
- For each set of simulated output time series we estimated their statistical characteristics and fitted a theoretical distribution, representing the parameter uncertainties, which is propagated from rainfall-runoff simulations.

7. Conclusions
- Improper representation of uncertainty is intrinsic drawback of all deterministic hydrological and water management models, which are prone to limited information provided by historical data (Efstratiadis et al., 2015).
- Combinations of hard (observations) and soft (human evidence based on experience) information can help reduce yet never eliminating uncertainties.
- Complex water-energy management problems suffer from multiple sources of uncertainties, since many of their inputs are not directly obtained from in situ measurements (e.g. rainfall) but are generated through models and sequences of models, where uncertainties are propagated from model to model.
- Stochastic approaches are unique means to quantify uncertainties, yet they do require careful interpretation of their outcomes, since they may result to tremendous uncertainty bounds that are difficult to take advantage in practice.

References