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Renewable energy and environmental systems: modelling, control and management for a sustainable future

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

Konstantinos Papoulakos, Giorgos Pollakis, Yiannis Moustakis, Apostolis Markopoulos, Theano Iliopoulou, Panayiotis Dimitriadis, Demetris Koutsoyiannis, and Andreas Efstratiadis

Contact info: papoulakoskon@gmail.com; poster info available at http://www.itia.ntua.gr/1682/

Department of Water Resources
& Environmental Engineering,
School of Civil Engineering,
National Technical University of
Athens, Greece

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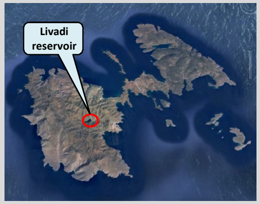
1. Abstract

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 in far from straightforward, since both the **availability and accuracy of associated information** is generally very poor. For, 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 management problem.

Using as example the Livadi reservoir, which is the **pumped storage component** of the **small Aegean island of Astypalaia**, Greece, we provide a simulation framework, 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, they 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

- Astypalaia (Αστυπάλαια) is a Greek island with 1334 residents (2011 census), that belongs to the Dodecanese complex (total area 97 km²).
- Livadi 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.

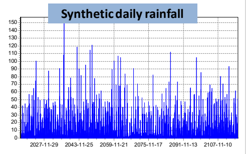


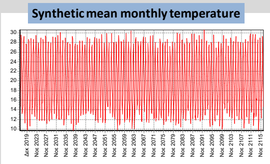
Key characteristics:
  - Catchment area 8 km²
  - Useful capacity 875 000 m³
  - Surface at max. elevation 105 000 m²

Water-energy components (hypothetical):
  - **Small hydropower plant**, installed at the discharge outlet (max head 32 m);
  - **Pump-storage tank**, implementing daily regulations of energy surpluses and deficits, provided by other renewables.

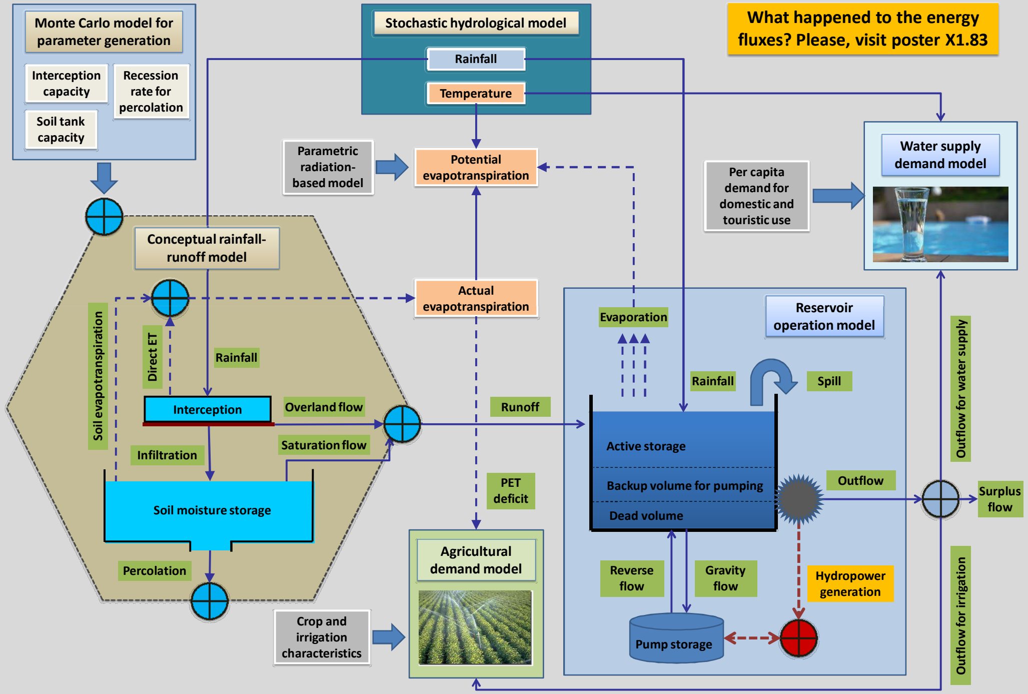
3. Representation of process uncertainty through stochastic simulation of key meteorological drivers

- Historical hydrometeorological 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 Castalia 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 (Hurst-Kolmogorov dynamics), periodicity and rainfall intermittency.



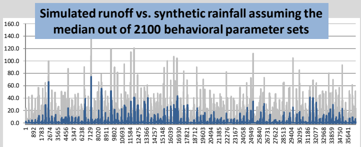


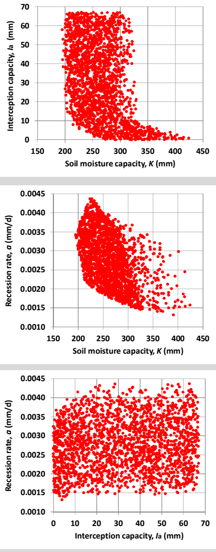
4. Outline of water-energy simulation procedure: data, models, parameters, processes



5. Monte Carlo approach for handling parameter uncertainty within runoff modelling

- Parsimonious modeling structure, using two daily input time series (rainfall , PET) and three parameters.
- Storage components, by means of **conceptual tanks**:
  - Interception tank of infinite capacity, accounting for temporary rainfall deficits within each day;
  - Soil tank of finite capacity, accounting for soil moisture storage fluctuations across 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**, I_a, 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**, a, 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 Penman-Monteith data from neighboring stations (Tegos *et al.*, 2013)
- **Overland flow** is estimated via a modified CN approach, where potential maximum retention is adjusted according to the varying soil moisture storage, while **saturated flow** is estimated by means of spill over the soil tank.
- Due to **lack of observed runoff** the model is subject to major uncertainty, expressed in terms of **a priori** distributions of parameters; for simplicity, I_a, K and a are considered **uniformly distributed within "reasonable" feasible ranges**.
- To reduce uncertainty, we take advantage of our **evidence** about the hydrological regime of Livadi catchment (**soft data**), thus accepting any parameter set ensuring mean annual percolation and runoff ratios between 10 and 20%.
- By employing **Monte Caro sampling** we detected 2100 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 providing 2100 **synthetic runoff scenarios** to the reservoir simulation model.

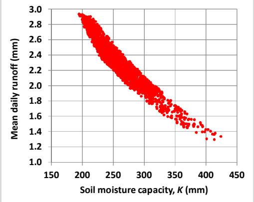




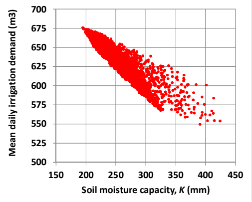
Scatter plots of all pairs of acceptable (behavioral) parameter sets

6. Reservoir management in stochastic setting

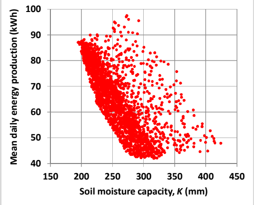
- Problem statement:
  - Fulfilment of water supply and irrigation demands;
  - Preservation of backup storage for employing energy regulations.
- Model **inputs** and associated **uncertainties**:
  - Catchment runoff, provided by the stochastic hydrological model (with uncertain parameters), driven 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 (>2100 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 uncertainty, which is **propagated from rainfall-runoff simulations**.



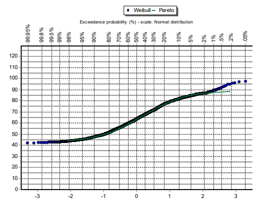
Mean daily runoff (output of hydrological model, input of reservoir model) vs. behavioral soil capacity values



Mean daily demand for irrigation (depends on simulated evapotranspiration deficits) vs. behavioral soil capacity values



Mean daily hydropower production vs. behavioral soil capacity values



Fitting of Pareto distribution to mean daily hydropower production values

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 reducing 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 or even sequences of models, where **uncertainties are propagated from model to model**.
- **Stochastic approaches** are unique means to quantifying 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

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