Hydrological modelling in presence of non-stationarity induced by urbanization: an assessment of the value of information

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Session Hw15: *Testing simulation and forecasting models in non-stationary conditions*

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1. Abstract

The proposed protocol of the workshop is followed, which regards the investigation of the effect of non-stationarity due to urbanization on the performance of a hydrological model. In particular, three rainfall-runoff models are employed in the tests: (i) a lumped daily model; (ii) a lumped monthly model; (iii) a parsimonious model of the conceptual type, based on the idea of Hydrological Response Units (HRU). In the latter, two HRUs are assumed that represent the urban and rural areas of the basin; the model is parameterized per HRU, with few parameters in each, as employed within the HYDROGEIOS framework (Efstratiadis *et al.*, 2008). A hybrid calibration approach is followed to obtain the best parameter set along with a large number of other retained sets. Levels 1 and 2 of the proposed protocol provide the necessary information for analysis of level 3, where a stochastic framework is considered, inspired by ideas proposed by Nalbantis *et al.* (2011) as well as Montanari & Koutsoyiannis (2012), which takes into account external information on urbanized fraction of the studied basin. A relationship is a priori considered between data on fraction of urbanized area and one of more parameters of the daily lumped model, while the HRU-based model takes into account the fraction of urbanized area explicitly. The methodology as a whole is applied to a drainage basin that shows growing urbanization, i.e. Ferson Creek at St. Charles, USA.

2. Study basin and data

- Ferson Creek at St. Charles (Chicago, USA); catchment area 134 km²;
- Data: precipitation (*P*), air temperature (*T*), PET, discharge (*Q*), from 1/1/1980 to 31/12/2011;
- Data providers: *Q*: USGS; *P* and *T*: DayMet, aggregated using the USGS Geo Data Portal; PET computed from *T* data, using the empirical formula by Oudin *et al.* (2005);
- Highly urbanized basin; fraction of urbanized area increased from 21.6% (1980) to 63.8% (2010); annual ratios are given as external information.

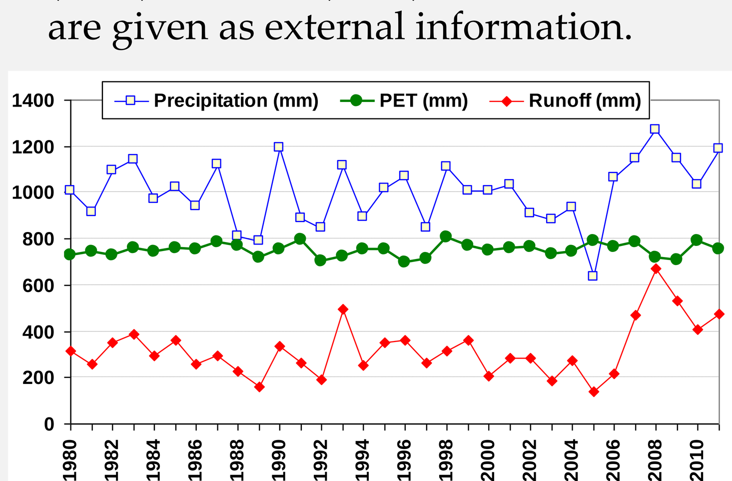

Fig. 1: Annual time series of *P*, PET and *Q* (1980-2011).

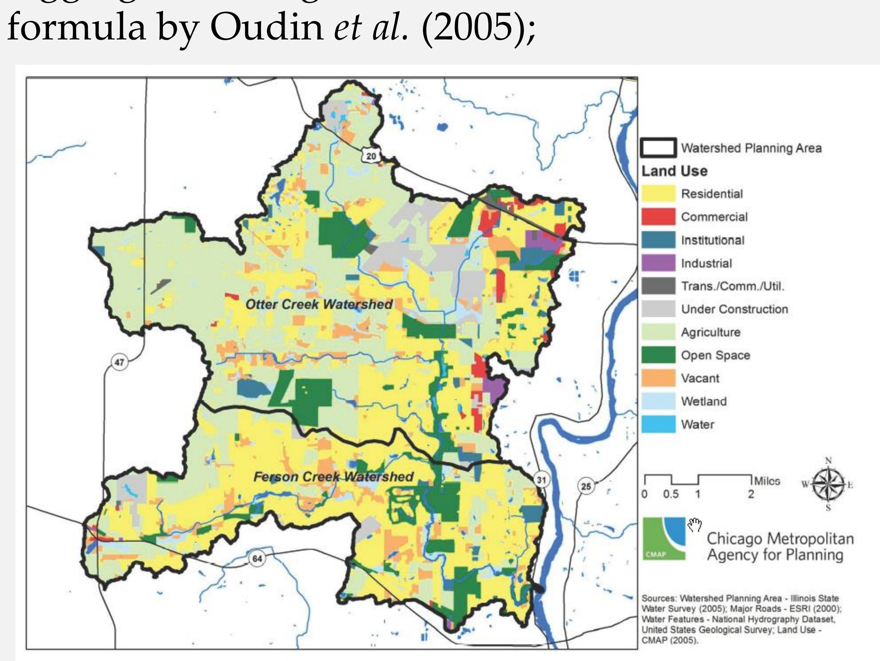

Fig. 2: Land use map (source: Chicago Metropolitan Agency for Planning, *Ferson-Otter Creek Watershed Plan*, 68 pp., Dec. 2011).

3. Deterministic modelling

General modelling framework

- Transformation of total precipitation into actual evapotranspiration, streamflow and underground flow;
- Usage of up to 12 parameters (3 for snow processes; 6 for surface hydrological processes; 3 for groundwater processes);
- Lumped expression of the semi-distributed modelling structure of HYDROGEIOS software.

Lumped daily version (12 parameters)

- Includes the module for snow accumulation and melting;
- Explicit dependence of direct runoff ratio, *c*, and time-varying urban area fraction, u_t, assuming that $c_t = c_0\, u_t$.

Lumped monthly version (9 parameters)

- Snow modelling is omitted, while urban area fraction is not accounted for.

HRU-based monthly version (15 parameters)

- Two HRUs are assumed with time-varying areas, urban and rural, thus explicitly representing the effects of urbanization to hydrological processes;
- Accumulated percolation by the two HRUs feeds a lumped groundwater tank.

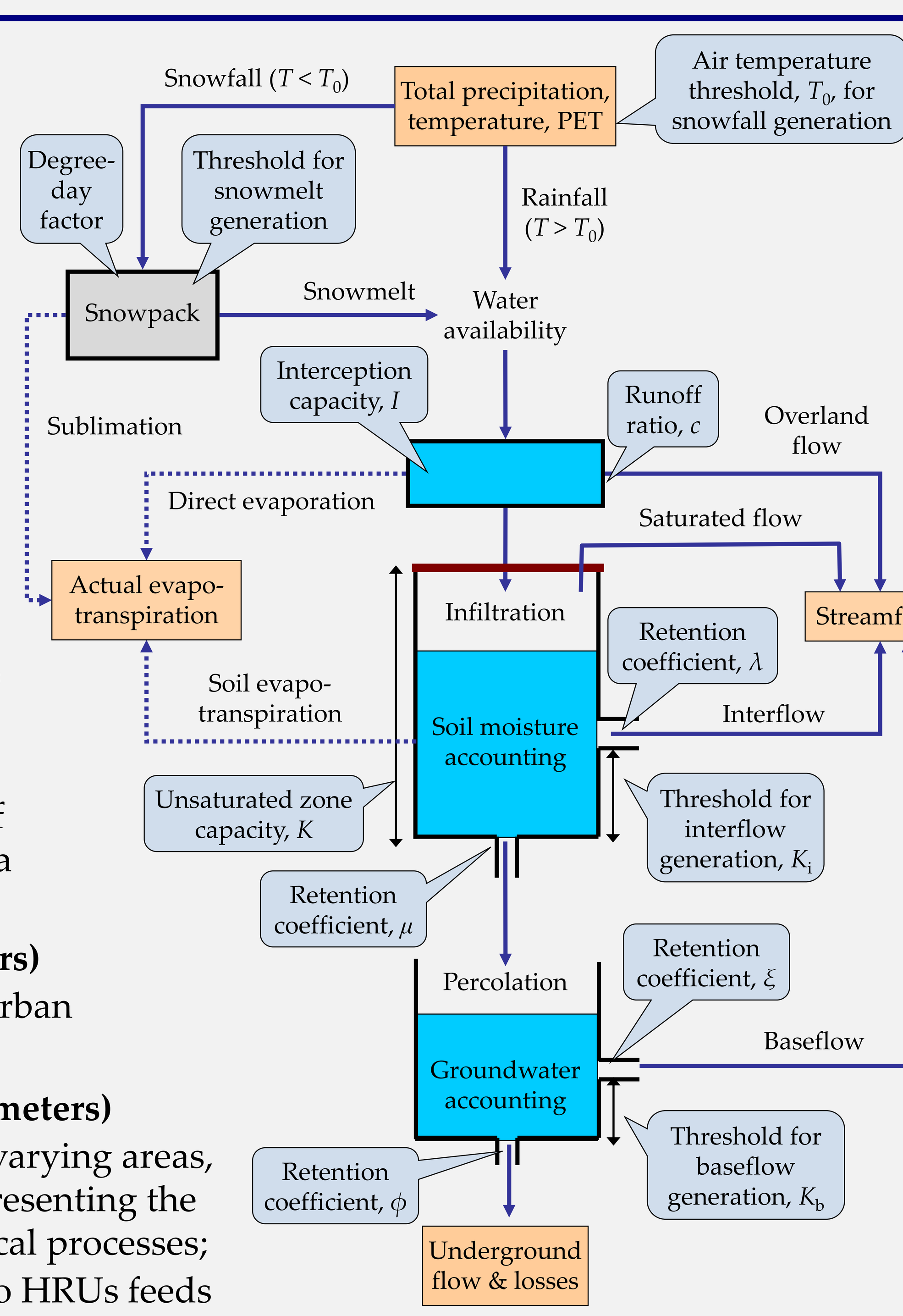

Fig. 3: Outline of the general modelling structure.

4. Stochastic modelling (Castalia software)

- *Open-access* software, for generating synthetic time series of hydrometeorological processes;
- Employs *multivariate stochastic simulation* at the *daily*, *monthly* and *annual* time scales;
- The model preserves, at all scales, the *marginal* (mean, variance, skewness) and *joint second order statistics* (i.e. auto- & cross-correlations); it also reproduces the *long-term persistence* (LTP, also referred to as Hurst-Kolmogorov dynamics) at the annual and over-annual scales, the *periodicity* at the monthly scale, and the *intermittency* at the daily scale.
- LTP is reproduced through a *symmetric moving average* (SMA) scheme for a *generalized autocovariance function* (GAF) with user-specified parameters (Koutsoyiannis, 2000), allowing to represent from ARMA-type ($H = 0.50$) to highly persistent processes ($H > 0.50$).
- Auxiliary series are provided by a multivariate PAR(1) scheme, both for the monthly and daily scales (Koutsoyiannis, 1999).
- A *disaggregation procedure* is employed to ensure statistical consistency between the three temporal scales; first the monthly series are adjusted to the known annual ones, and next the daily time series are adjusted to the disaggregated monthly ones (Koutsoyiannis, 2001).

5. Testing framework (levels 1 & 2)

Protocol level 1: Single parameterization

- Calibration efforts for the daily lumped model gave low values (in general, less than 50%) of the Nash-Sutcliffe efficiency (NSE) criterion.
- The monthly models exhibited much better performance; the lumped one resulted to 66.3% efficiency, while the HRU-based version provided a NSE value of 76.6%, with reasonable parameter values (parameter set 0).

Protocol level 2: Multiple parameterizations

- At this level, we kept only the best out of 3 models, i.e. the HRU-based monthly one, for which we employed individual calibrations and cross-validations, by dividing the whole data period into five sub-periods.
- Results are given by means of a 6 × 6 matrix of efficiency values for the six parameter sets; as expected, the highest NSE are obtained during calibration; yet, the model performance is slightly only deteriorated during the four validation sub-periods, which indicates high robustness.

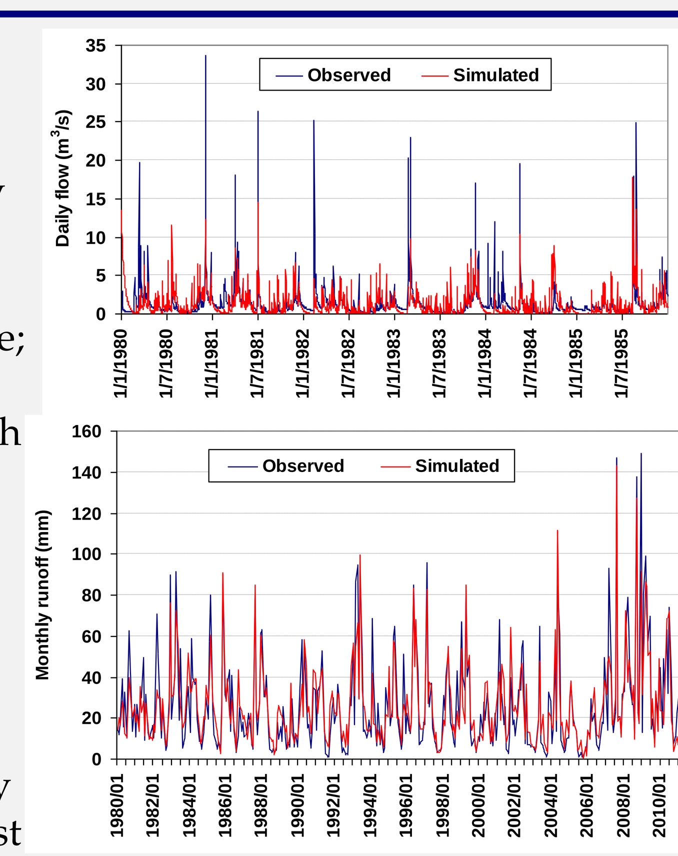

Fig. 4: Observed vs. simulated runoff for daily (up; sub-period 1/1980 – 5/1986) and monthly, HRU-based, model (down; full data period).

Table 1: NSE values across different data periods and corresponding parameter sets; diagonal elements refer to optimized efficiency criteria (obtained via calibration), while off-diagonal elements are validation values.

	From	To	Parameter set 0	Parameter set 1	Parameter set 2	Parameter set 3	Parameter set 4	Parameter set 5
Period 0	Jan-80	Dec-12	0.766	0.739	0.746	0.746	0.742	0.717
Period 1	Jan-80	May-86	0.705	0.739	0.649	0.688	0.598	0.604
Period 2	Jun-86	Oct-92	0.737	0.586	0.777	0.619	0.747	0.438
Period 3	Nov-92	Mar-99	0.798	0.788	0.757	0.833	0.764	0.788
Period 4	Apr-99	Aug-05	0.714	0.617	0.738	0.622	0.764	0.584
Period 5	Sep-05	Dec-12	0.755	0.748	0.727	0.752	0.731	0.796

6. Combined use of stochastic & deterministic models (level 3)

- Initially, we generated 1000 years of synthetic time series of monthly *P*, PET and *Q*, through Castalia.
- The GAF were estimated on the basis of the empirical autocorrelograms; first order autocorrelations are negligible for *P* and PET, but they are significantly for *Q*, indicating a remarkable Hurst-Kolmogorov behaviour.
- The Hurst coefficients for the three simulated variables are 0.60 (precipitation), 0.55 (PET) and 0.74 (runoff).
- In this approach, an elementary physical consistency between *P*, PET and *Q* is ensured, since the observed cross-correlations are reproduced in the synthetic data.
- On the other hand, the long-term variability of runoff is not properly accounted for, as the changing conditions due to urbanization are embedded in the historical data.

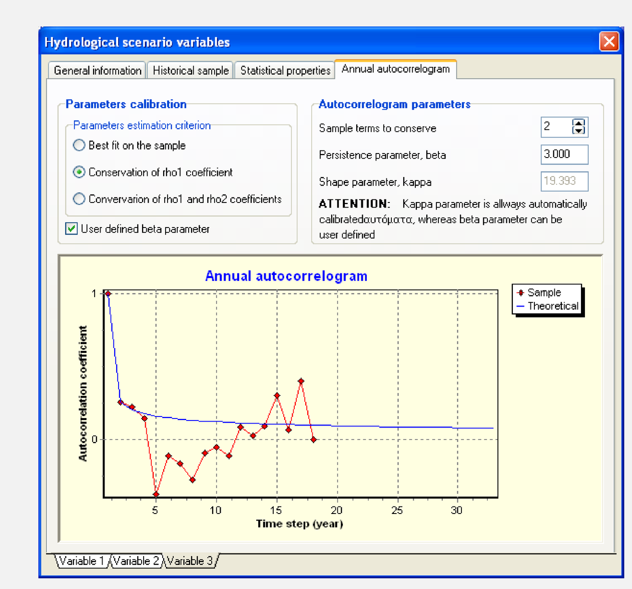

Fig. 6: Fitting of theoretical autocovariance function of annual runoff to the empirical one.

- In order to distinguish non-stationary effects due to human effects (i.e. growing urbanization), we employed a two-step procedure, by using *P* and PET data provided by Castalia to the deterministic hydrological model, for estimating *Q* through stochastic simulation, assuming a constant urbanization fraction of 66% for the whole simulation period (1000 years).
- The Hurst coefficient of *Q* was reduced to 64%; this difference is the part of runoff persistence that is due of urbanization, which should not be accounted for in stochastic simulations.

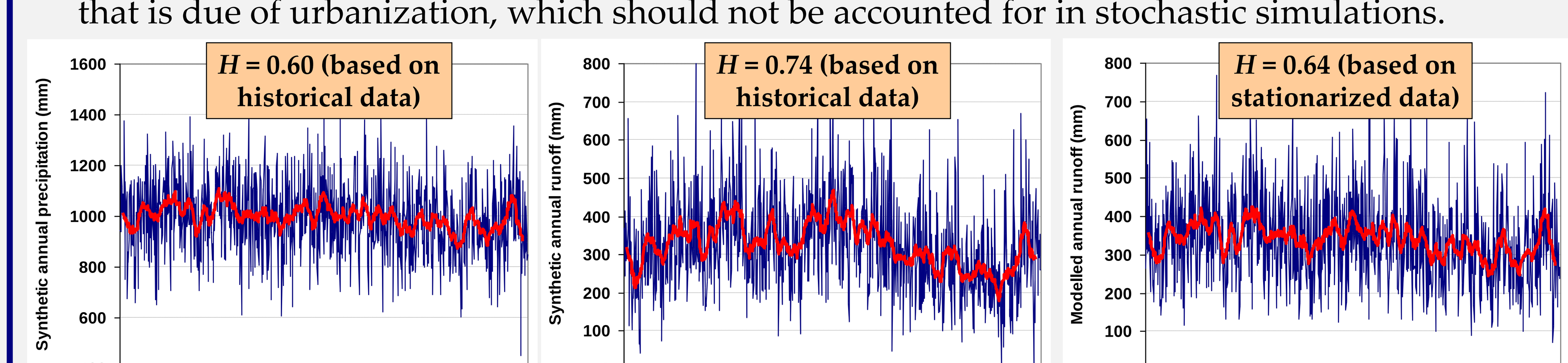

Fig. 7: Annual time series, 20-year moving average and Hurst coefficients of synthetic precipitation (left), synthetic runoff (centre) and simulated, through the deterministic hydrological model with synthetic precipitation and PET, runoff (right).

7. Conclusions

- The proper way to face changing conditions in runoff series due to urbanization proved to be the explicit inclusion of this effect in hydrological models; in particular, the concept of dynamically evolving HRUs, with changing surface areas, was found to be easy and efficient.
- The combined use of stochastic simulation and the explicit inclusion of the fraction of urbanized area in the model helped to stationarize the runoff process and thus assess the part of streamflow persistence that is due to natural causes and the part that is due to urbanization.
- Since model exploitation in water management studies requires that (a) anthropogenic effects, such as urbanization, are considered known (either stabilized or changing in time), and (2) a large period is simulated, the use of stochastic models, for generating the hydrological inputs, and deterministic models that represent the human interventions in modified basins, seem to be the only alternative for providing realistic and statistically consistent simulations.

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