How to adapt a nonurban model structure to account for urbanization?

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Context and objectives

TIA: mean total impervious area, taken as the arithmetic mean of percent impervious surface from catchment pixels

Evolution from a slightly urbanized to an intensively urbanized situation

Rural model: does not take account of any urban-specific feature/process

Urbanized model: one that takes into account the presence of urbanized surfaces within the catchment
**Context and objectives**

**Question**: How to modify the structure of the rural model to better reproduce the rainfall-runoff relationship at the scale of urbanized catchments, with different levels of imperviousness?

Rural model: does not take account of any urban-specific feature/process

Urbanized model: one that takes into account the presence of urbanized surfaces within the catchment
Types of attempted adaptations

The type of model adaptation depends on the specificities of the rural model (complexity, choice of process representation)

- **Implicit / Lumped**
  - **Choice of process representation**
  - **Model complexity (number of parameters)**

- **Limited number of parameters**
  - **Type of adaptation**
    - Relate model parameters to urbanization measures
      - **Examples**: ReFH (Kjeldsen, 2007; Kjeldsen et al., 2013)
  - Add an «imperviousness branch» to the rural model
    - **Examples**: Aronica et Cannarozzo (2000), MUSIC (Dotto et al., 2011; Hamel et Fletcher, 2014), KAREN (Dotto et al., 2011)
  - Add an imperviousness branch + other anthropic processes (e.g., potable water, sewerage system, irrigation...)
    - **Examples**: SIMHYD (Singh et al., 2009), Aquacyle (Mitchell et al., 2001)
  - Explicit representation of urban-induced processes
    - **Examples**: ISBA-TOPMODEL (Furusho et al., 2013); TEB-Hydro (Stavropulos-Laffaille et al., 2018)
Methodology: “trial-error” approach, guided by data analysis

Hypotheses
To explain

Conceptualization

Formulation

Test and evaluation

Model
To make testable/to test hypotheses

Data
To formulate and test hypotheses

Model
To make testable/to test hypotheses

Data
To formulate and test hypotheses
- A sample of 175 urbanized catchments (i.e., mean total impervious area TIA > 10%), located in the US (156) and France (19).

- Each catchment has a minimum of 8 years of hourly hydroclimatic data between 1997-2017 (median = 16 years).

- TIA available each 3-5 years on average: NLCD for US, CLMS for France.

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (km²)</td>
<td>1.1</td>
<td>726.4</td>
</tr>
<tr>
<td>Mean precipitation  $P_m$ (mm/year)</td>
<td>500</td>
<td>1620</td>
</tr>
<tr>
<td>Mean potential evapotranspiration  $PE_m$ (mm/year)</td>
<td>630</td>
<td>1400</td>
</tr>
<tr>
<td>$P_m/PE_m$</td>
<td>0.6</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Starting rural model

Rural hydrological model: GR4H (Ficchi et al., 2019; Le Moine et al., 2008)

**Inputs (mm)**
- **P**: Precipitation depth
- **E**: Potential evapotranspiration depth

**GR4H parameters**
- **I**$_{\text{max}}$, **X**$_1$, **X**$_3$: Reservoir capacities (mm)
- **X**$_2$: Potential exchange parameter (mm/h)
- **X**$_4$: Base time of unit hydrographs (h)

**GR4H states (mm)**
- **I**, **Prod**, **Rout**: Reservoir states

**GR4H internal fluxes and outputs (mm)**
- **E**$_{i}$, **E**$_{s}$, **AE**: Actual evapotranspiration
- **P**$_{\text{th}}$: Throughfall
- **P**$_{s}$: Infiltration
- **Perc**: Percolation
- **PR**: Net precipitation
- **Q**$_9$, **Q**$_1$: Outputs of UH1 and UH2
- **F**: Potential exchange with groundwater
- **Q$_r$**: Slow flow
- **Q$_d$**: Quick flow
- **Q**: Total flow

Process-based, continuous, lumped, hourly model
Developed using large international samples of rural catchments
Starting rural model

Rural hydrological model: GR4H (Ficchi et al., 2019; Le Moine et al., 2008)

Production: Interception + soil moisture accounting (production) reservoir
Net precipitation PR divided as such 10% of PR goes through quick flow routing branch and 90% of PR through slow flow routing branch
Hydroclimatic data analysis: event runoff ratio

~37000 events from the 175 catchments
Events are grouped by catchment, by year, and by season, to compute the mean RR

Formulation

A production dependent on TIA?

\[
RR = 0.48 \times \text{TIA} + 0.1, \quad r^2 = 0.19
\]

\[
RR = 0.5 \times \text{TIA} + 0.05, \quad r^2 = 0.25
\]

\[
RR = 0.52 \times \text{TIA} + 0.02, \quad r^2 = 0.35
\]

\[
RR = 0.54 \times \text{TIA} + 0.02, \quad r^2 = 0.34
\]
Hydroclimatic data analysis: Baseflow Index

Formulation

Relative importance of baseflow dependent on TIA?

\[ BFI = \frac{\sum_h Q^h_b}{\sum_h Q^h} \]
Tested modifications

Conceptualization

Production

1-TIA

TIA

Production – pervious surfaces

Production – impervious surfaces

Production – pervious surfaces

Production – impervious surfaces

Based on runoff ratio

Based on BFI
Tested modifications

Conceptualization

Production – pervious surfaces
- Quick flow
- Slow flow

Production – impervious surfaces
- Quick flow
- Slow flow

Production – pervious surfaces
- 1-TIA
- TIA

Production – impervious surfaces
- 1-TIA
- TIA

All splits optimized

Based on runoff ratio

Based on BFI

Rural model

TIA-split

TIA-split and optimized routing

1-X₆

X₆

1-X₅

X₅

PR

P

5/2/2020
Tested modifications: number of calibrated parameters

- Conceptualization
- Production
  - Pervious surfaces
    - Quick flow
    - Slow flow
    - 4 parameters
  - Impervious surfaces
    - Production
      - 1-TIA
      - TIA
      - PR
      - 1 - X_6
      - X_6
      - 5 parameters
      - 6 parameters
Assessing the relevance of tested modifications

<table>
<thead>
<tr>
<th>Year 1</th>
<th>...</th>
<th>Year N/2 - 1</th>
<th>Year N/2</th>
<th>Year N/2 + 1</th>
<th>...</th>
<th>Year N</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P2</td>
</tr>
</tbody>
</table>

- **Calibration algorithm**: a broad inspection of the model parameter hyperspace, followed by a gradient descent algorithm (Edijatno et al., 1999)

- **Objective function (OF)**: Kling-Gupta Efficiency $KGE$ (Gupta et al., 2009)

$$KGE = 1 - \sqrt{(1 - r)^2 + (1 - \alpha)^2 + (1 - \beta)^2}$$

- Correlation
- Ratio of standard deviations
- Ratio of means

Test and evaluation
## Assessing the relevance of tested modifications

<table>
<thead>
<tr>
<th>Type of assessment criterion</th>
<th>Criterion</th>
<th>Abbreviation</th>
<th>Ideal value</th>
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</thead>
</table>
| **Continuous** (2 periods* 175 catchments) | Nash-Sutcliffe of discharges  
Focus on dry conditions  
Focus on wet conditions | NSE  
NSE DRY  
NSE WET | 1 |
| **Event-based** (~37000 events) | Error in peakflow estimation | $\varepsilon_{Q_p}$ | 1 |
|  | Error in event runoff volume | $VE$ | 1 |

\[
NSE = 1 - \frac{\sum_h (Q_{sim}^h - Q_{obs}^h)^2}{\sum_h (Q_{obs}^h - Q_{obs})^2}
\]

\[
\varepsilon_{Q_p} = 1 - \frac{|Q_{sim}^p - Q_{obs}^p|}{Q_{obs}^p}
\]

\[
VE = 1 - \frac{\sum_{h \in event} |Q_{sim}^h - Q_{obs}^h|}{\sum_{h \in event} Q_{obs}^h}
\]

$sim$: simulated, $obs$: observed, $Q^h$: discharge at hour h, $Q^p$: peakflow
## Calibration performances

<table>
<thead>
<tr>
<th>Structure</th>
<th>Number of parameters</th>
<th>Median KGESQ (square root values)</th>
<th>Median KGE (non-transformed values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural model</td>
<td>4</td>
<td>0.88</td>
<td>0.85</td>
</tr>
<tr>
<td>TIA-split</td>
<td>4</td>
<td>0.89</td>
<td>0.87</td>
</tr>
<tr>
<td>TIA-split and optimized routing</td>
<td>5</td>
<td>0.89</td>
<td>0.88</td>
</tr>
<tr>
<td>All splits optimized</td>
<td>6</td>
<td>0.90</td>
<td>0.88</td>
</tr>
</tbody>
</table>

More degrees of freedom (i.e., calibrated parameters) results in better calibration performances. Improved calibration by uniquely adding information from TIA.
Adding an impervious branch results in better NSE performances, especially when focus is put on dry conditions.

Event peakflow estimation is also ameliorated, as well as event runoff volume estimation.

Optimizing both splits gives the best overall results.
**Conclusion**

**Question**: How to modify the structure of the rural model to better reproduce the rainfall-runoff relationship at the scale of urbanized catchments, with different levels of imperviousness?

At the catchment scale, adding a pervious / impervious split + an optimized slow flow/quick flow split improves the rainfall-runoff relationship
Conclusion

**Question:** How to modify the structure of the rural model to better reproduce the rainfall-runoff relationship at the scale of urbanized catchments, with different levels of imperviousness?

When the split parameters are set free, regionalization is needed to use the urbanized model for future scenarios prediction.
Cited references


