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

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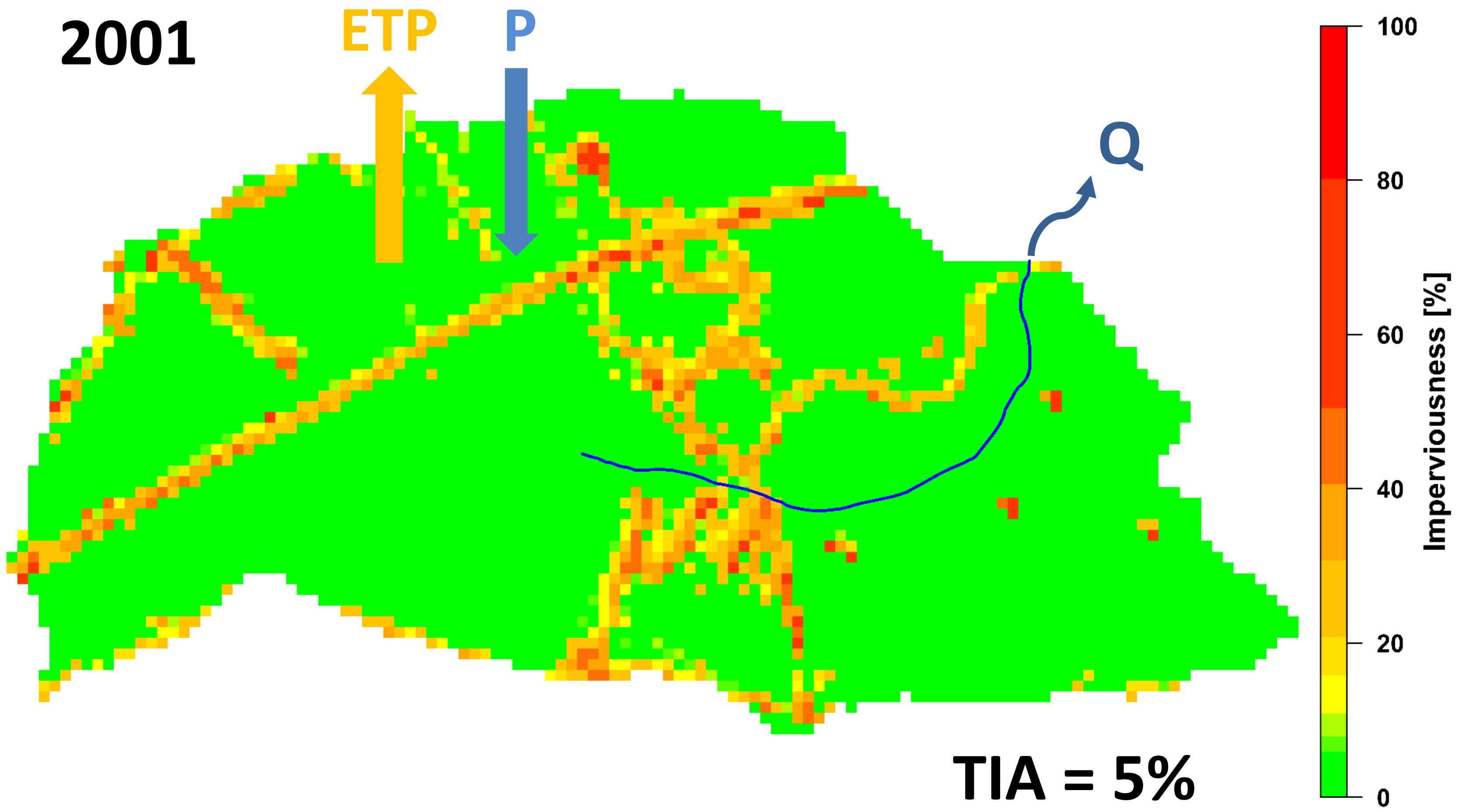
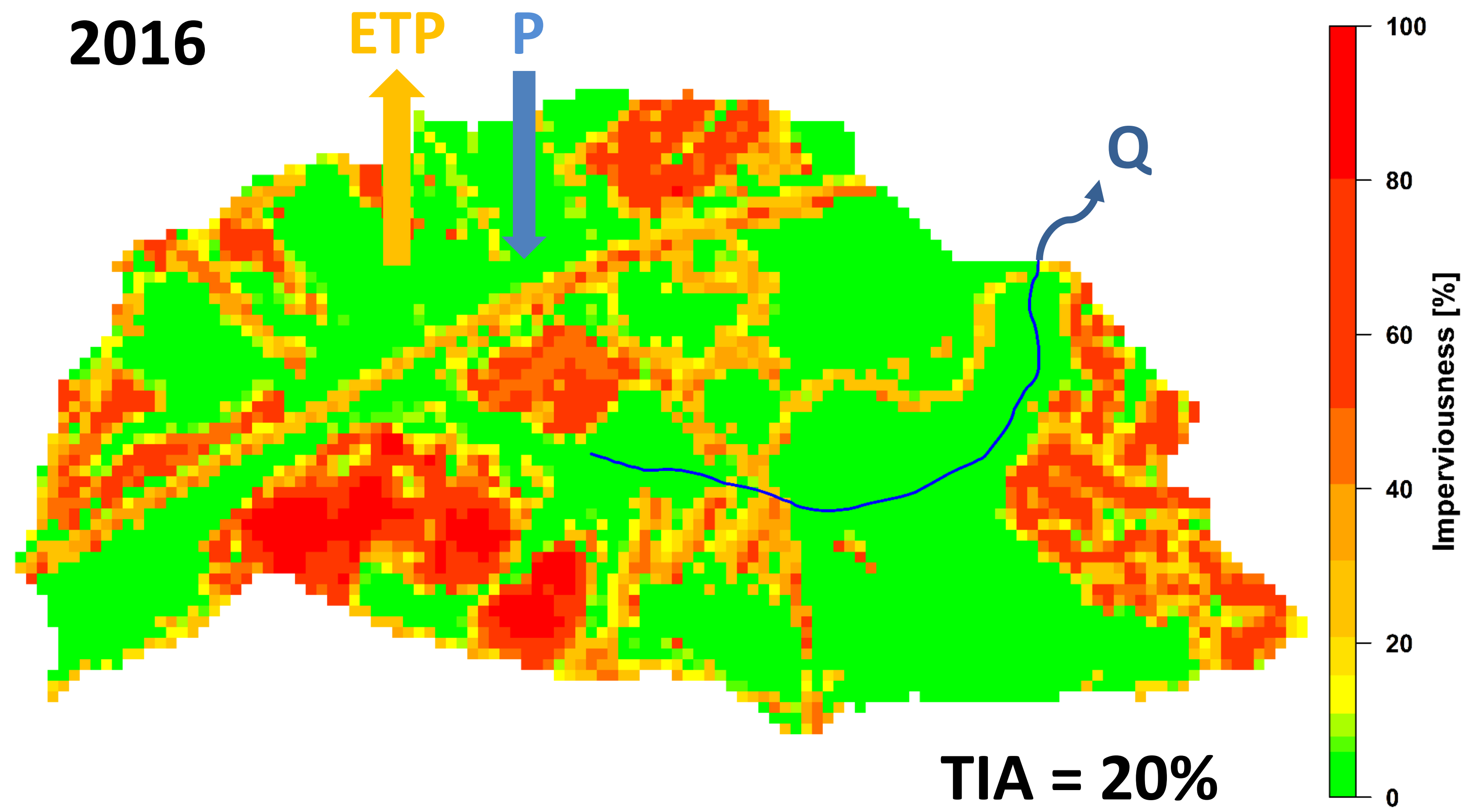
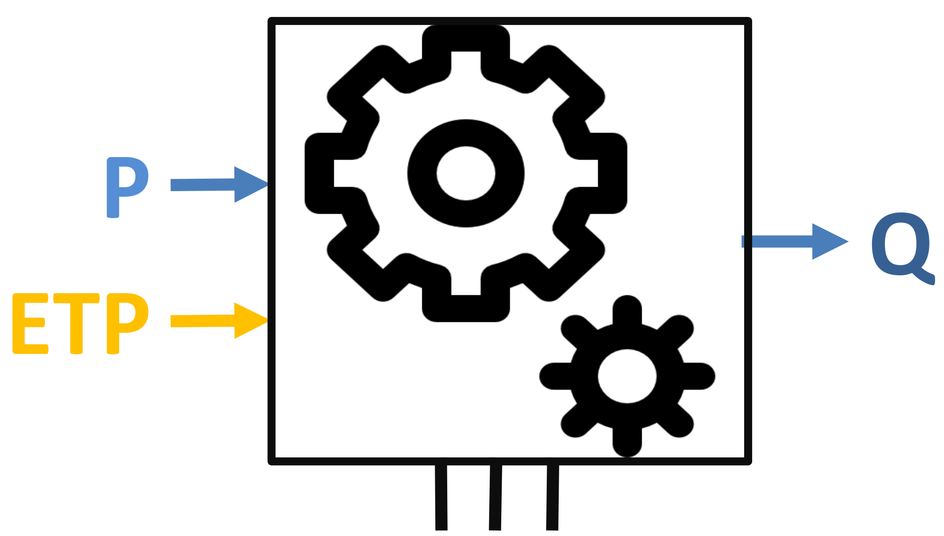
Context and objectives





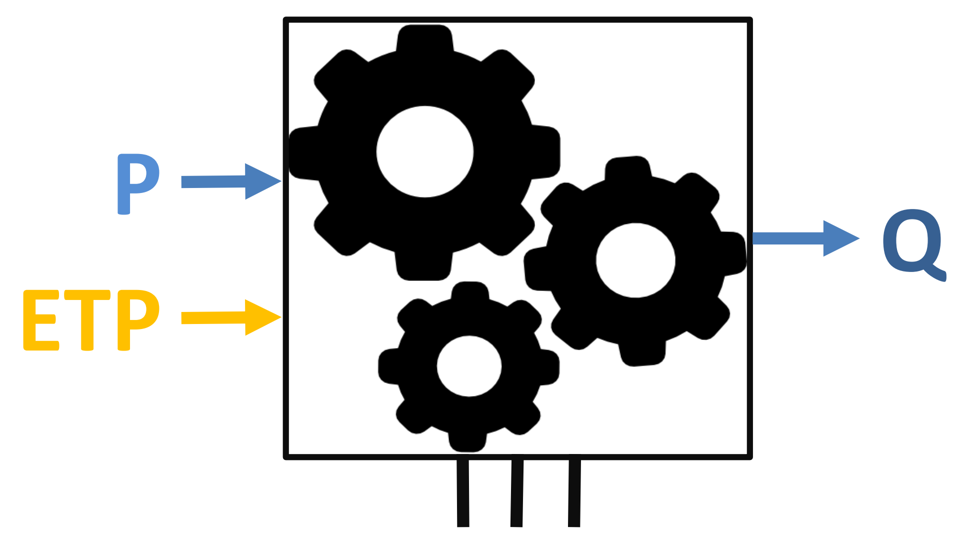
TIA: mean total impervious area, taken as the arithmetic mean of percent impervious surface from catchment pixels

Evolution from a **slightly urbanized** to an **intensively urbanized** situation



$\boldsymbol{f}(P, ETP, \{\theta\})$

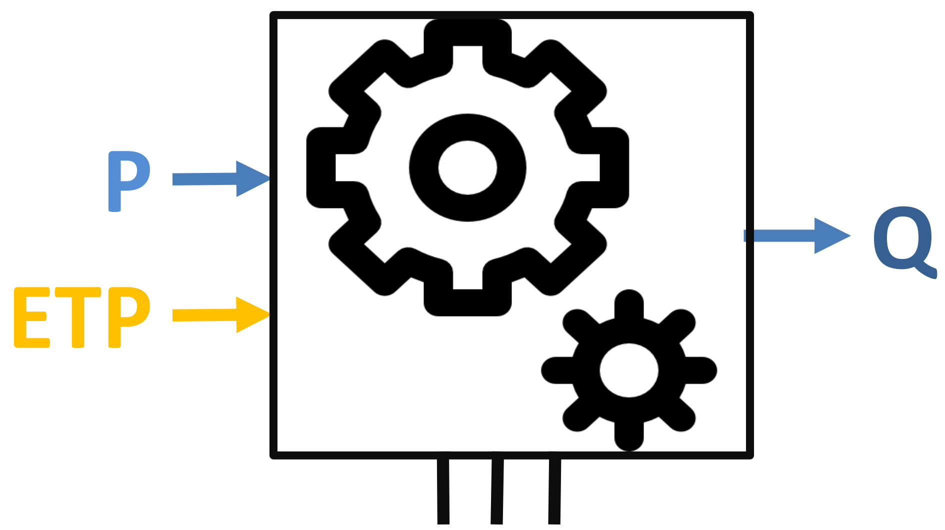
Rural model: does not take account of any urban-specific feature/process



$\boldsymbol{g}(P, ETP, \{\theta\}, \{\theta\}_{Urb})$

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

Context and objectives



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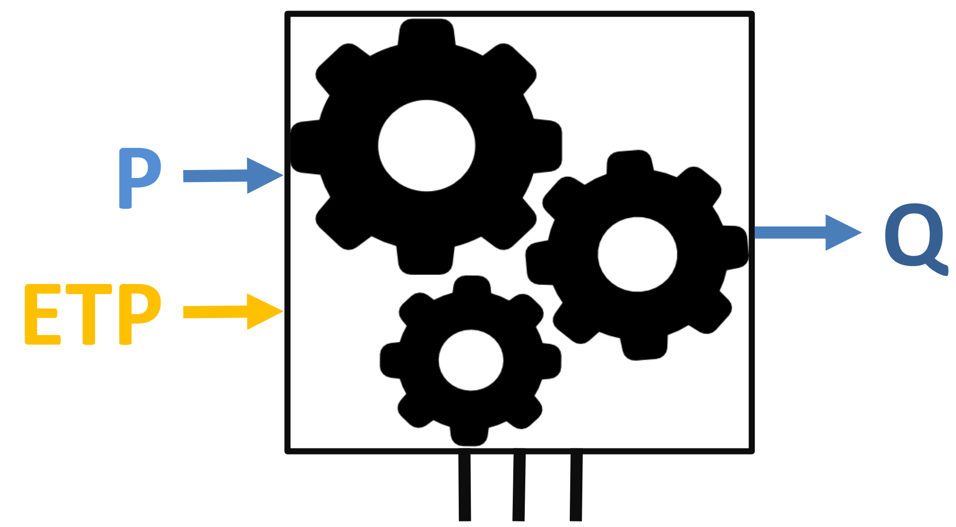
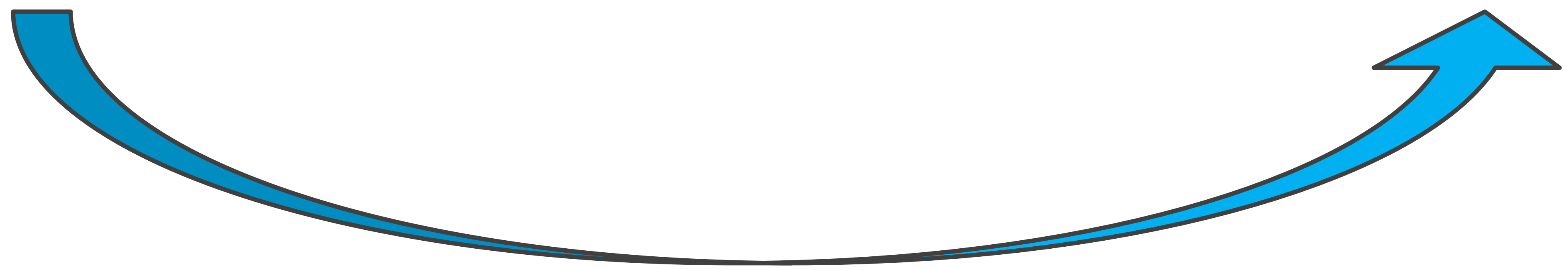


$g(P, ETP, \{\theta\}, \{\theta\}_{Urb})$

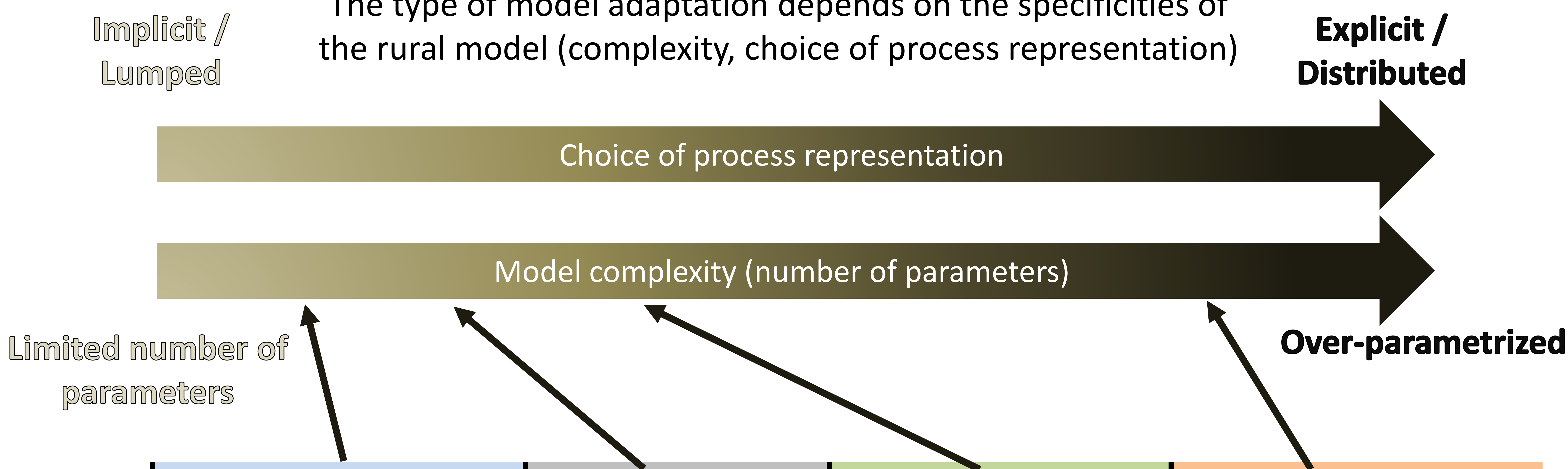
Urbanized model: one that takes into account the presence of urbanized surfaces within the catchment



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?

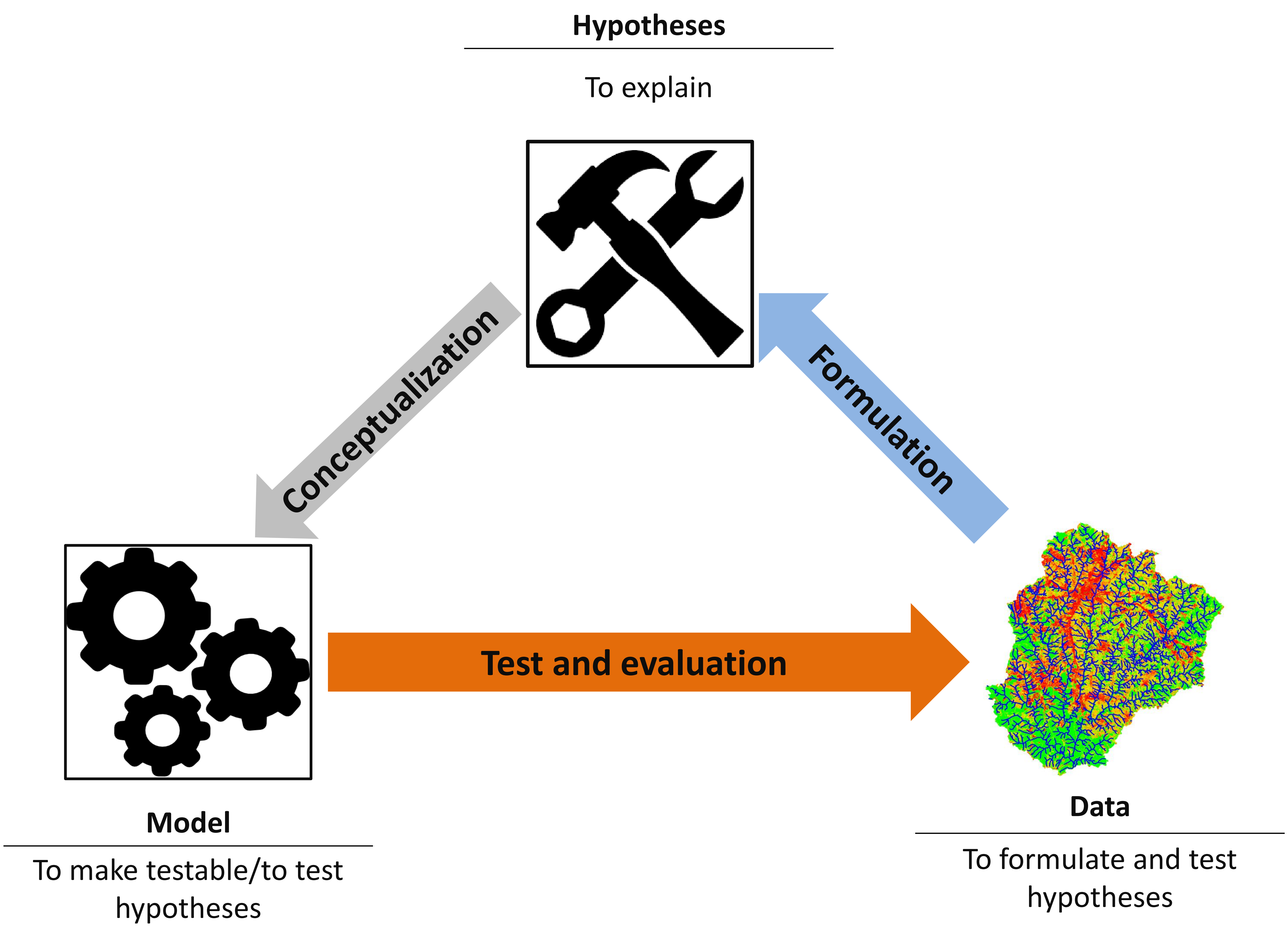
Types of attempted adaptations

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

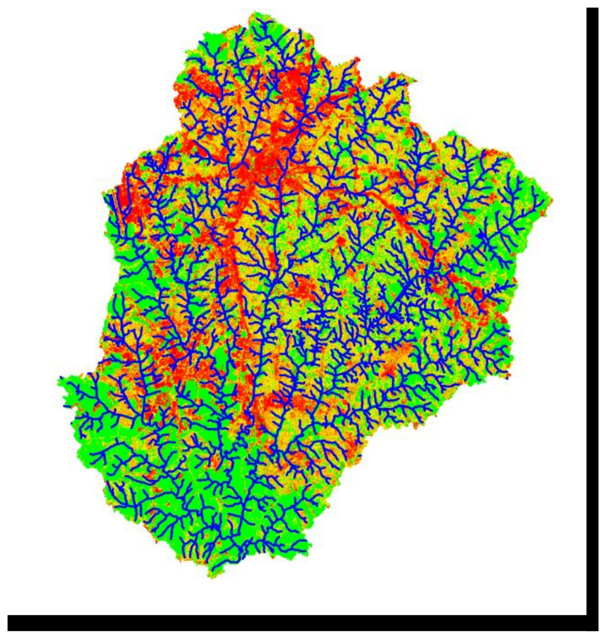


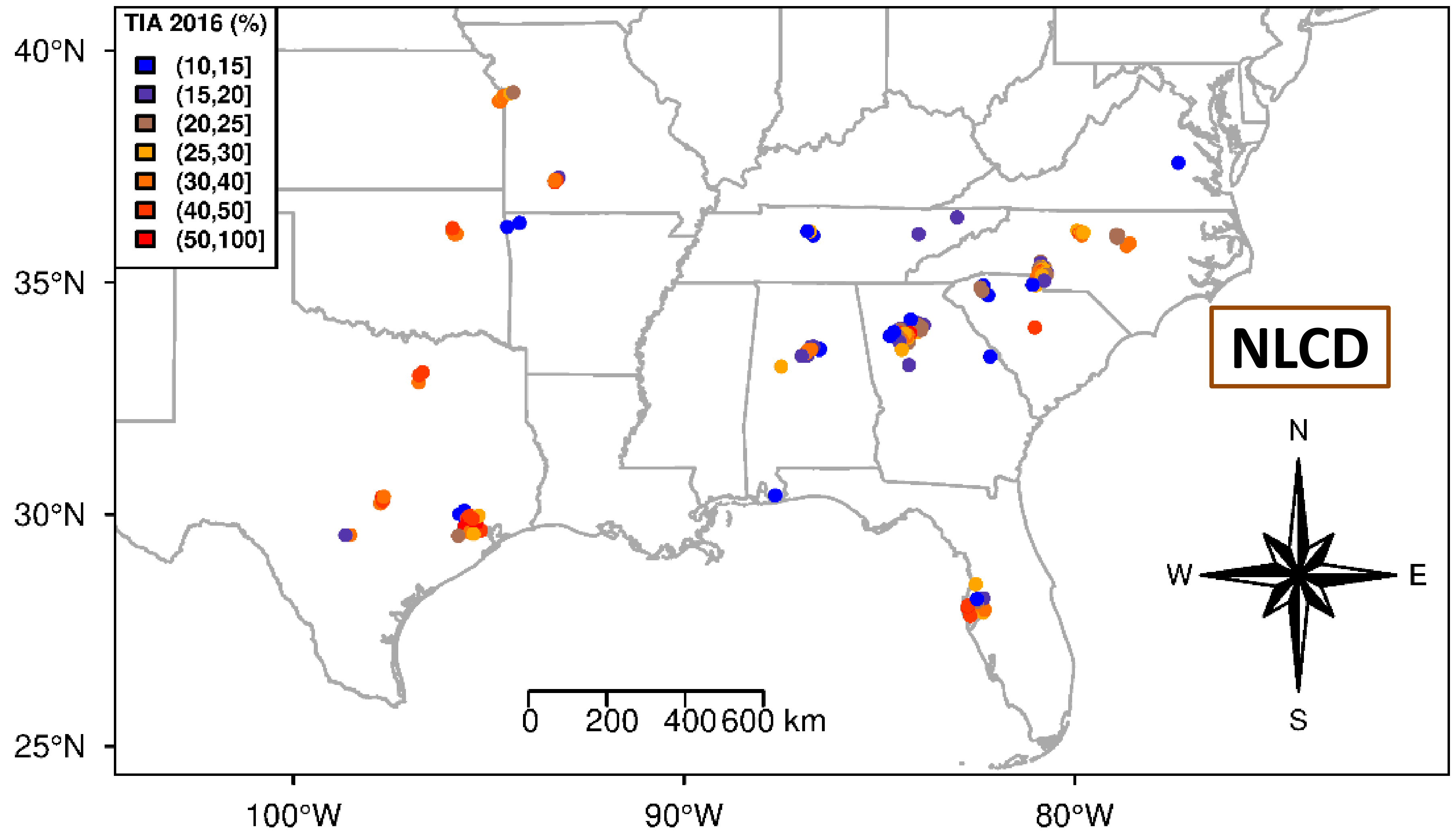
Type of adaptation	**Relate model parameters to urbanization measures**	**Add an «imperviousness branch» to the rural model**	**Add an imperviousness branch + other anthropic processes (e.g., potable water, sewerage system, irrigation…)**	**Explicit representation of urban-induced processes**
Examples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

Methodology: “trial-error” approach, guided by data analysis



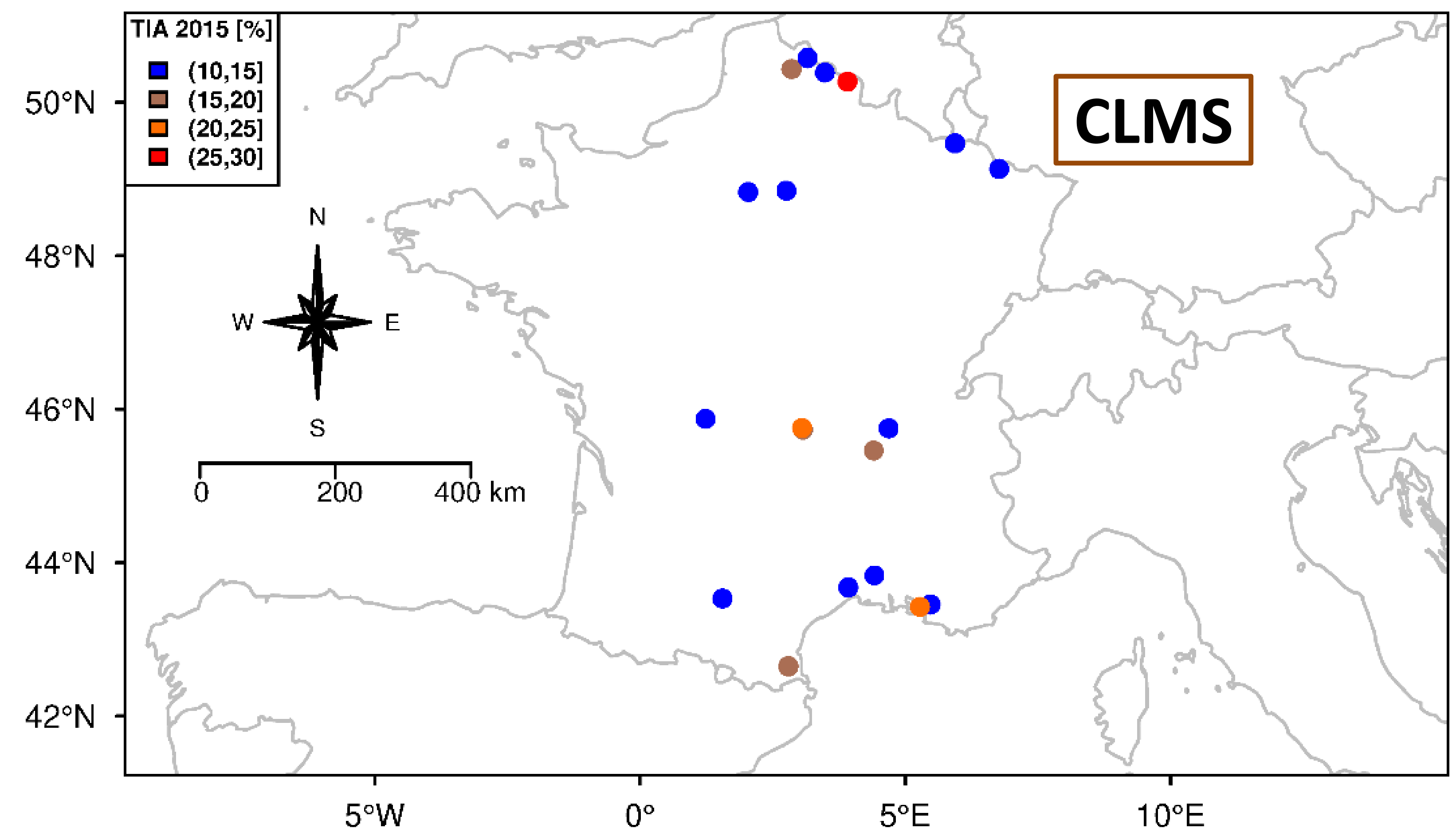
Data: catchment sample



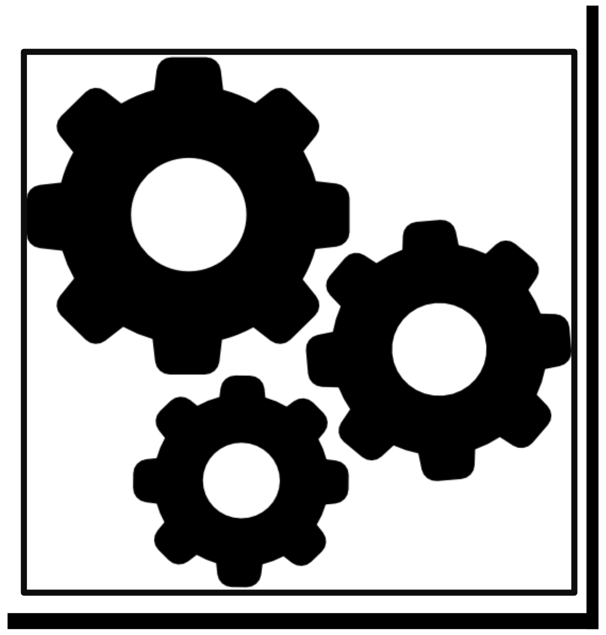


- **A sample of 175 urbanized catchments (i.e., mean total impervious area TIA > 10%), located in the US (156) and France (19)**
- **Each catchment has a minimum of 8 years of hourly hydroclimatic data between 1997-2017 (median = 16 years)**
- **TIA available each 3-5 years on average: NLCD for US, CLMS for France**

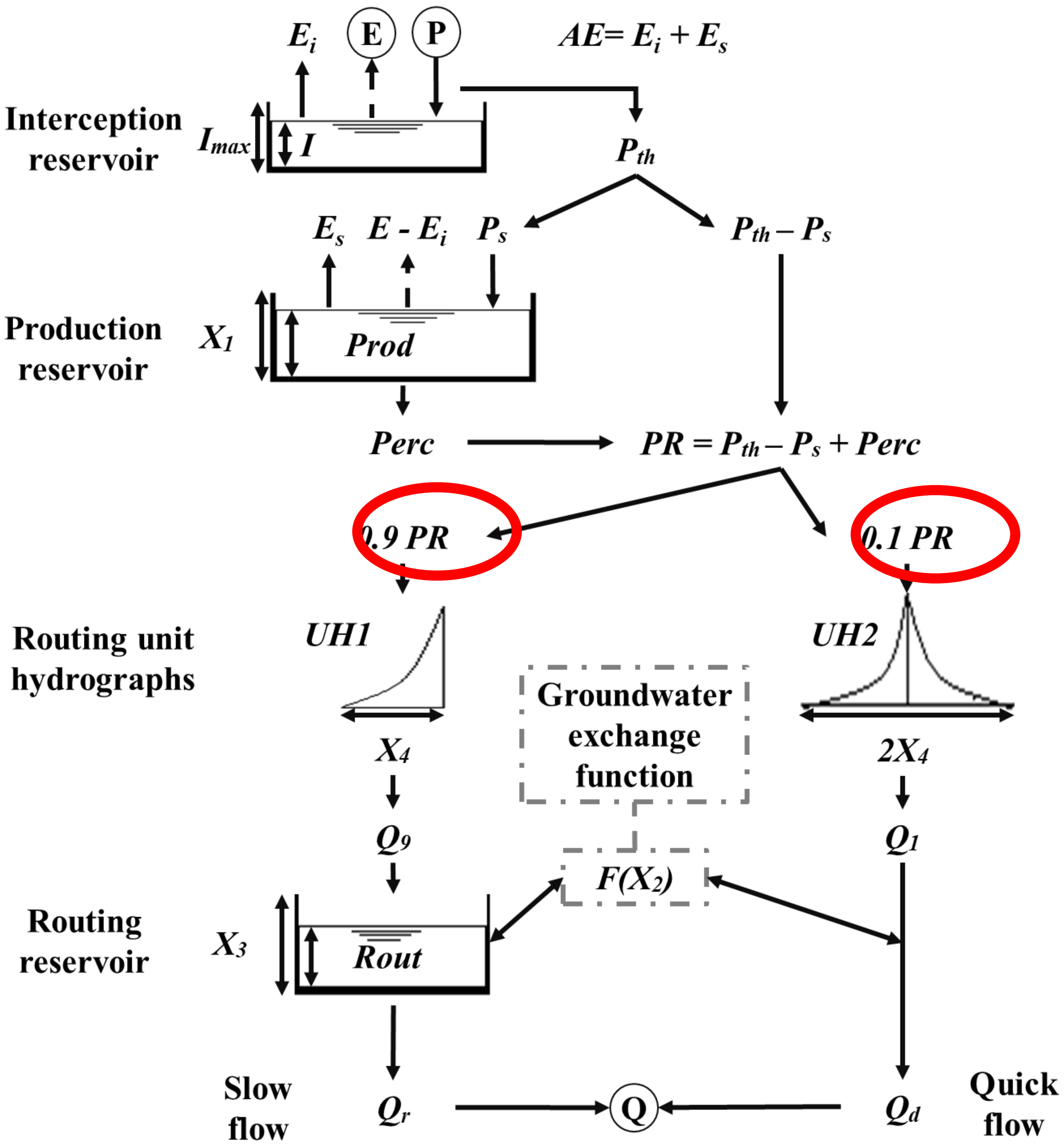
	Min	Max
Area (km²)	1.1	726.4
Mean precipitation P_m (mm/year)	500	1620
Mean potential evapotranspiration PE_m (mm/year)	630	1400
P_m/PE_m	0.6	1.5



Starting rural model



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



Inputs (mm)

P: Precipitation depth

E: Potential evapotranspiration depth

GR4H parameters

I_{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_{th}: Throughfall

P_s: Infiltration

Perc: Percolation

PR: Net precipitation

Q_9, Q_1: Outputs of UH1 and UH2

F: Potential exchange with groundwater

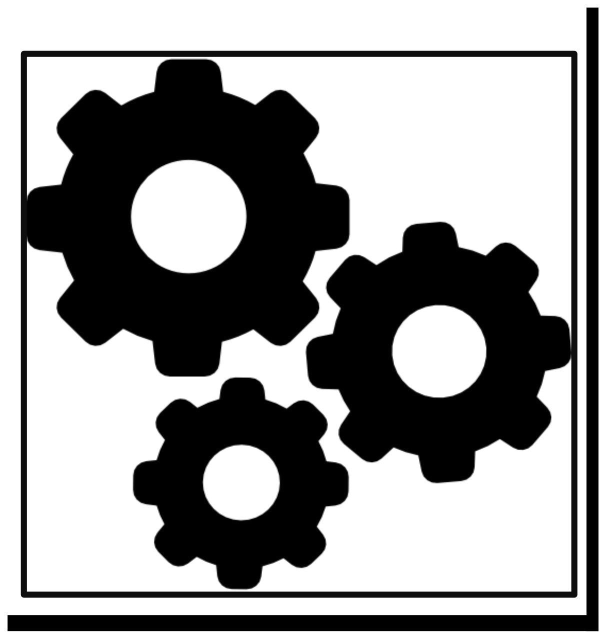
Q_r: Slow flow

Q_d: Quick flow

Q: Total flow

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

Starting rural model



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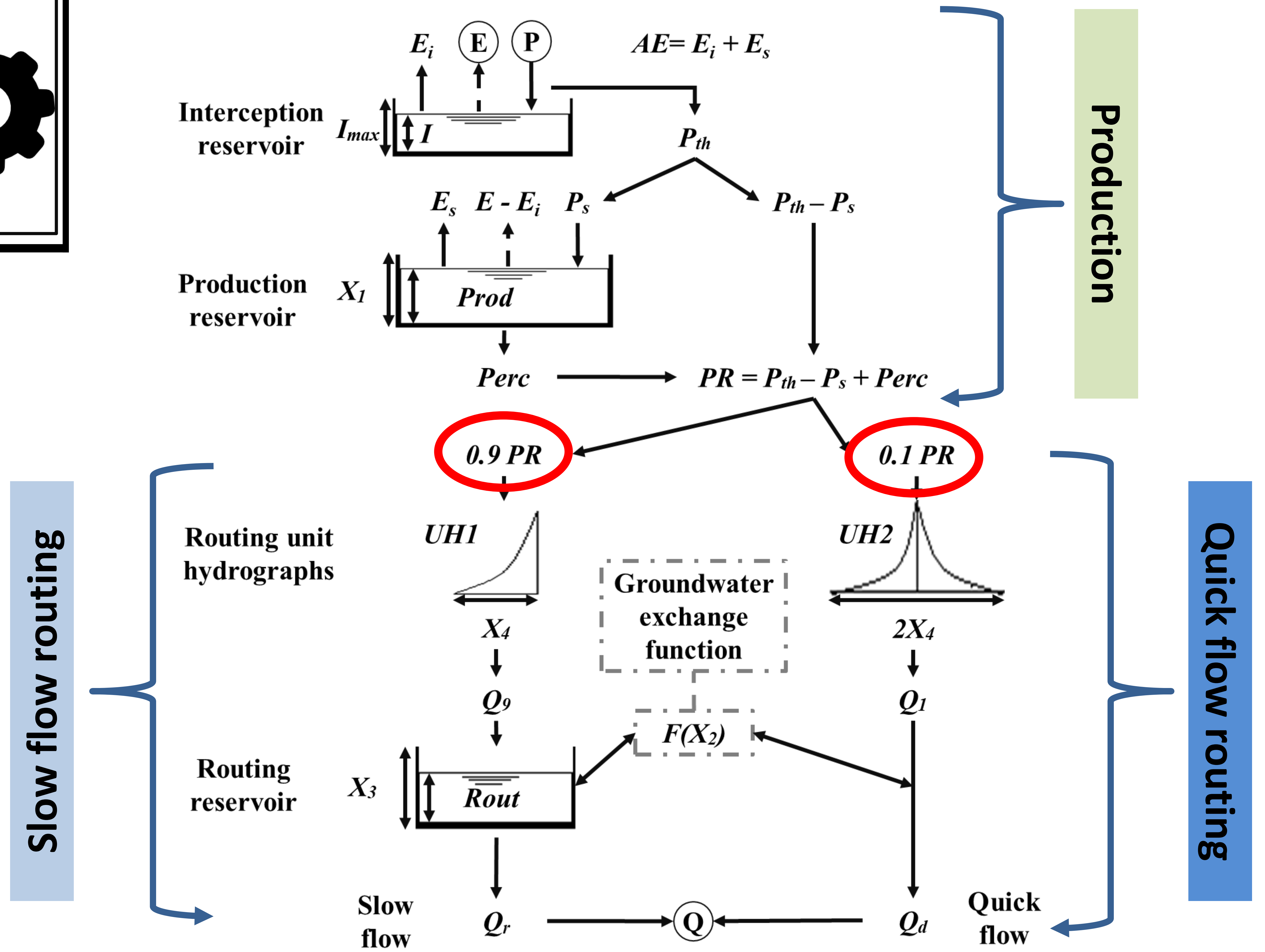
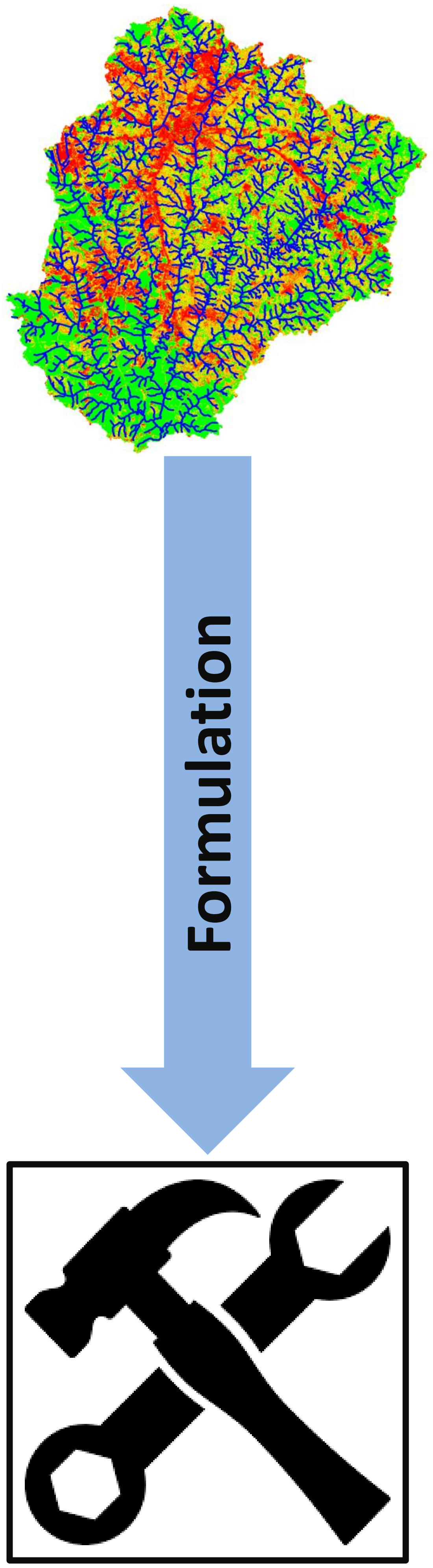


Production: Interception + soil moisture accounting (production) reservoir

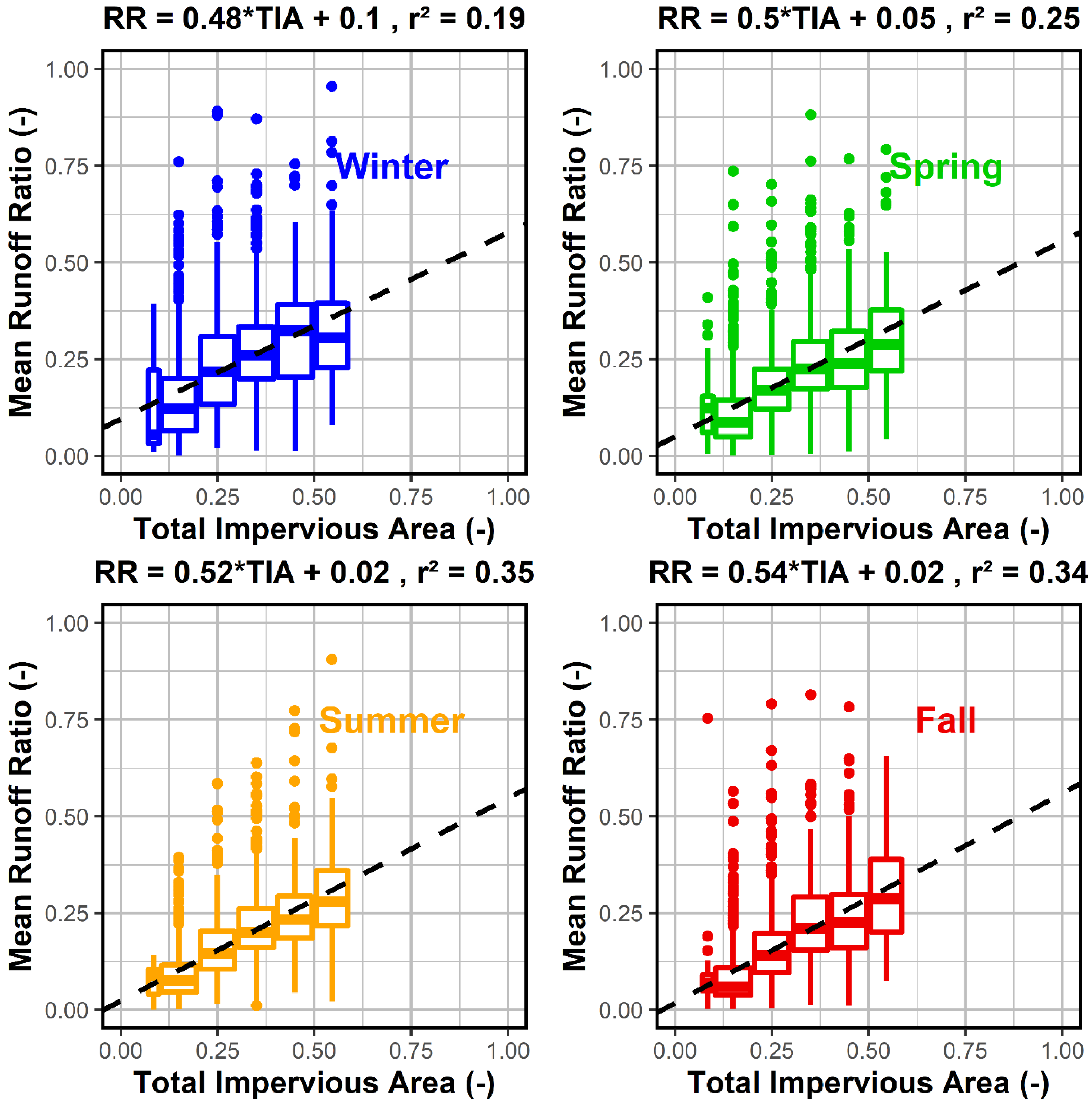
Net precipitation PR divided as such 10% of PR goes through quick flow routing branch and 90% of PR through slow flow routing branch

Hydroclimatic data analysis: event runoff ratio



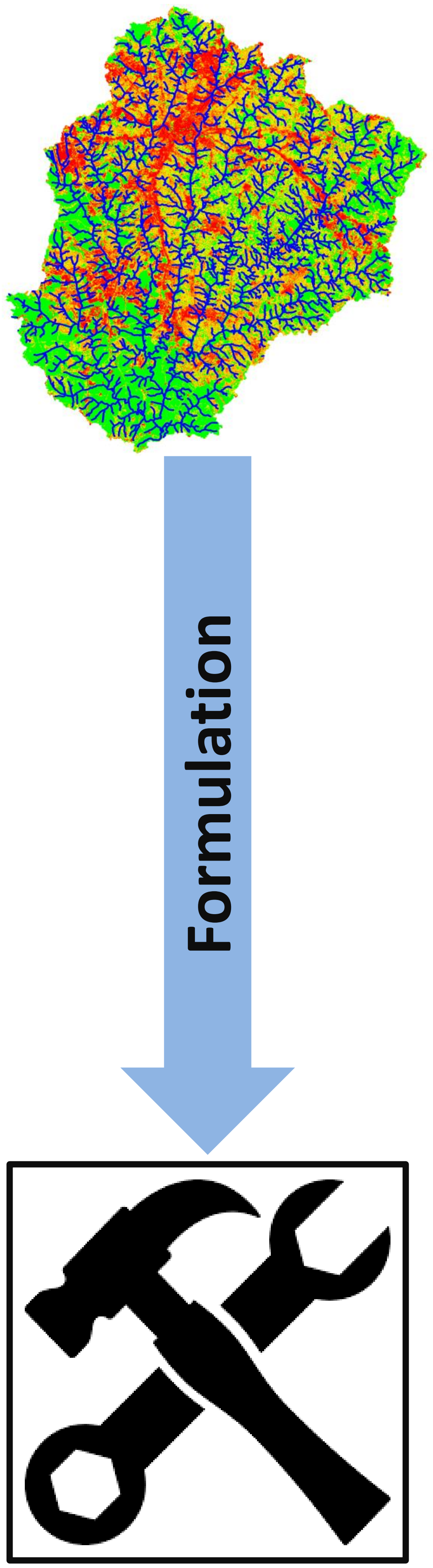
~37000 events from the 175 catchments

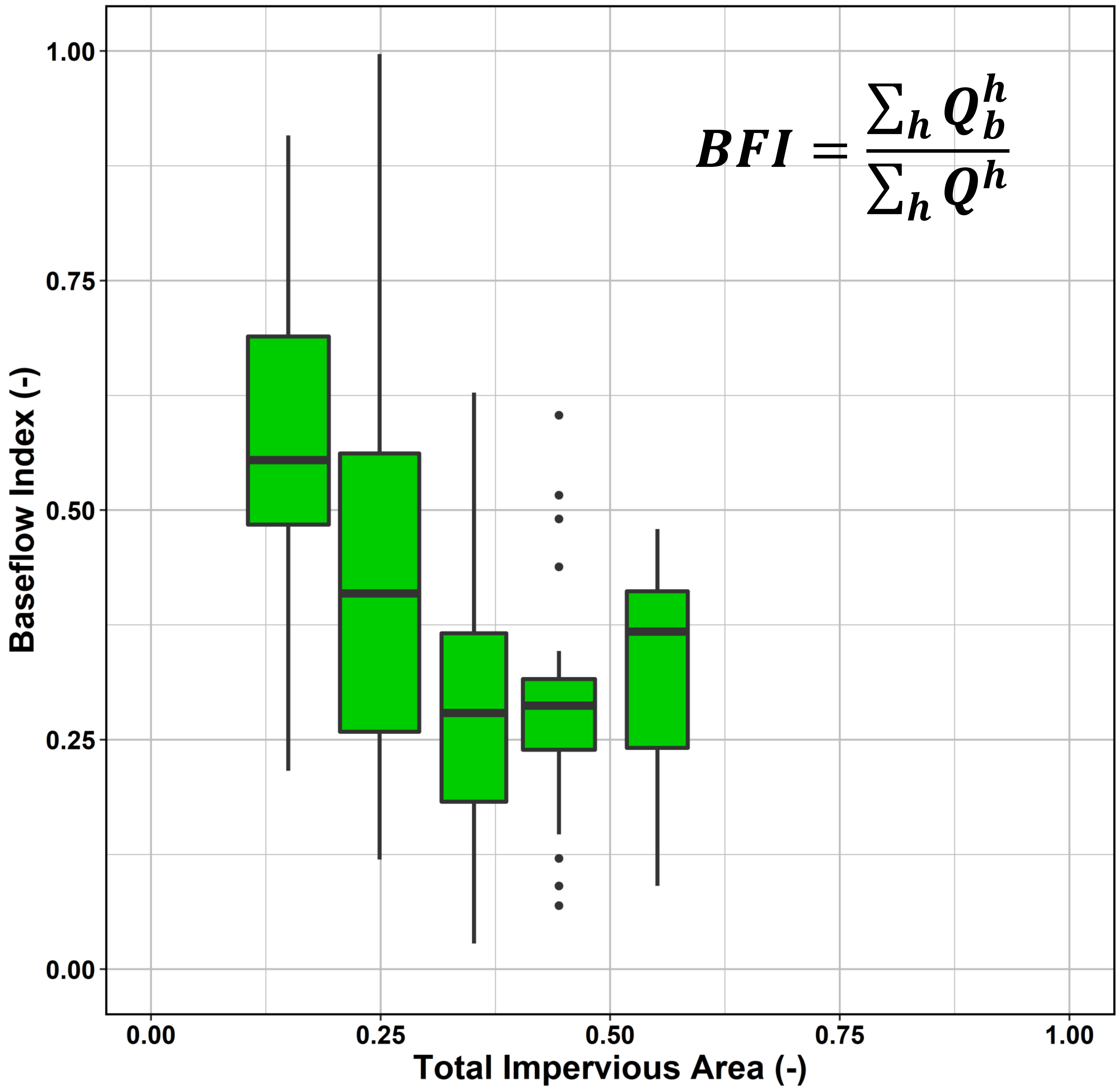
Events are grouped by catchment, by year, and by season, to compute the mean RR



A production dependent on TIA?

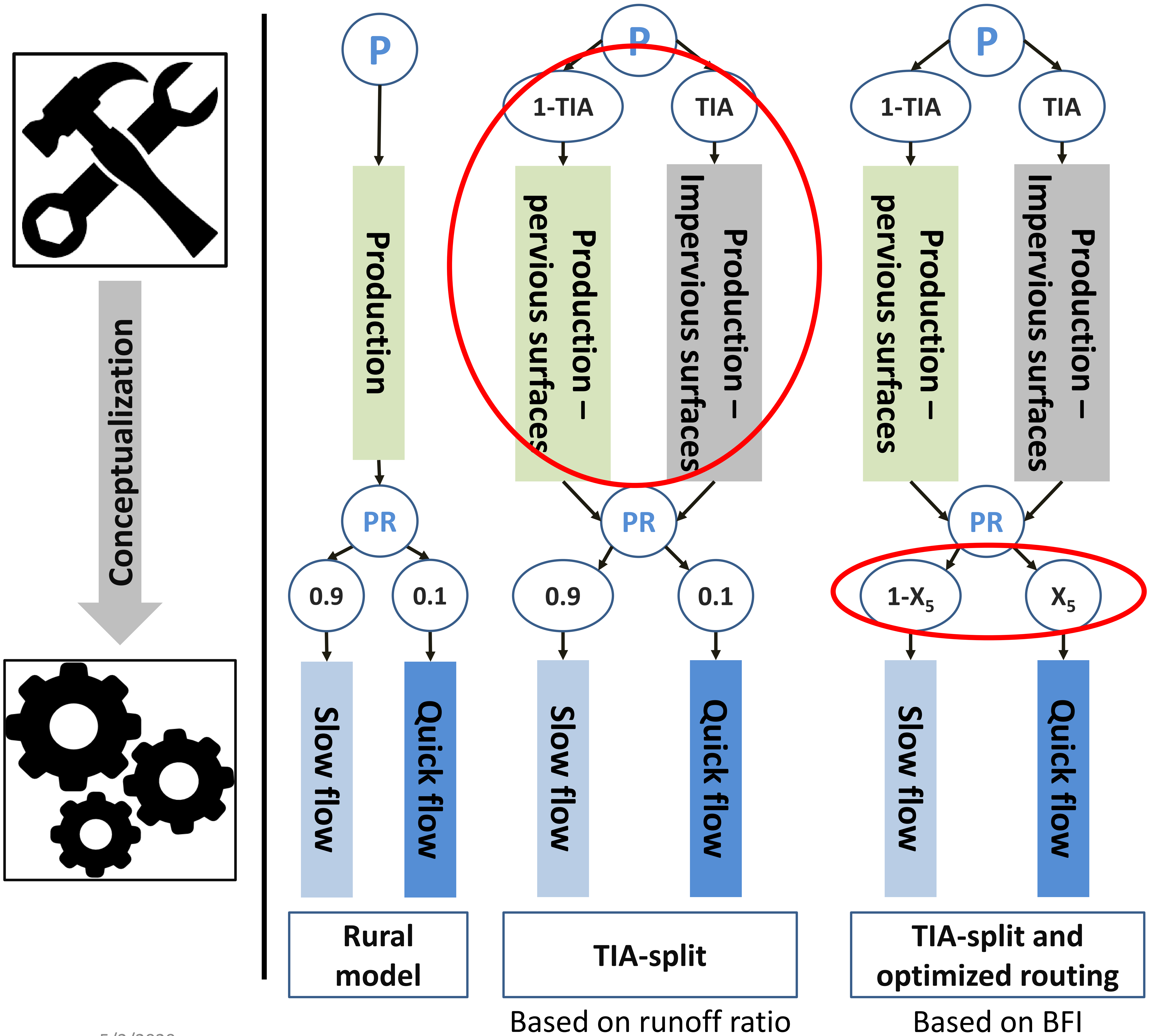
Hydroclimatic data analysis: Baseflow Index





Relative importance of baseflow dependent on TIA?

Tested modifications



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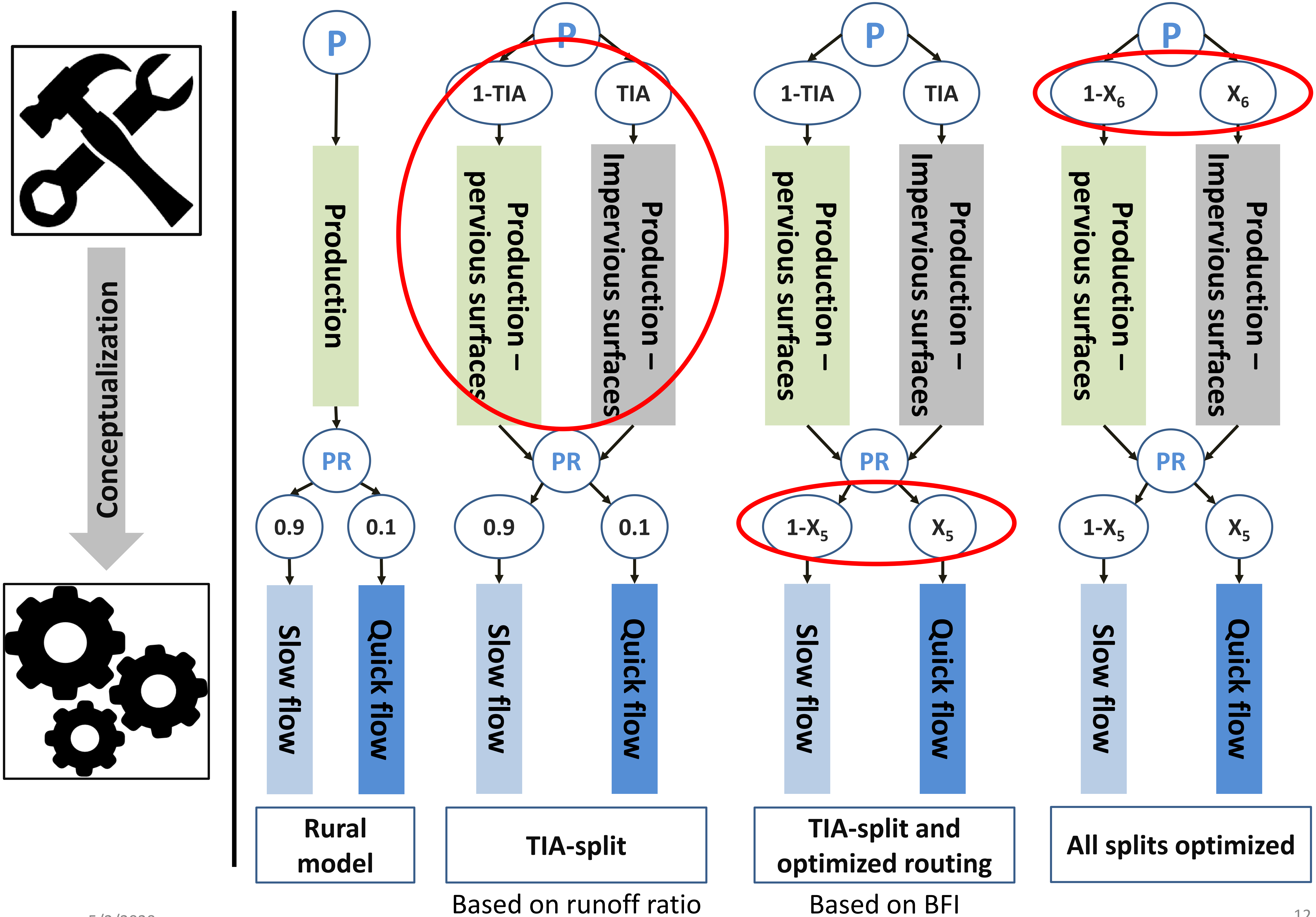
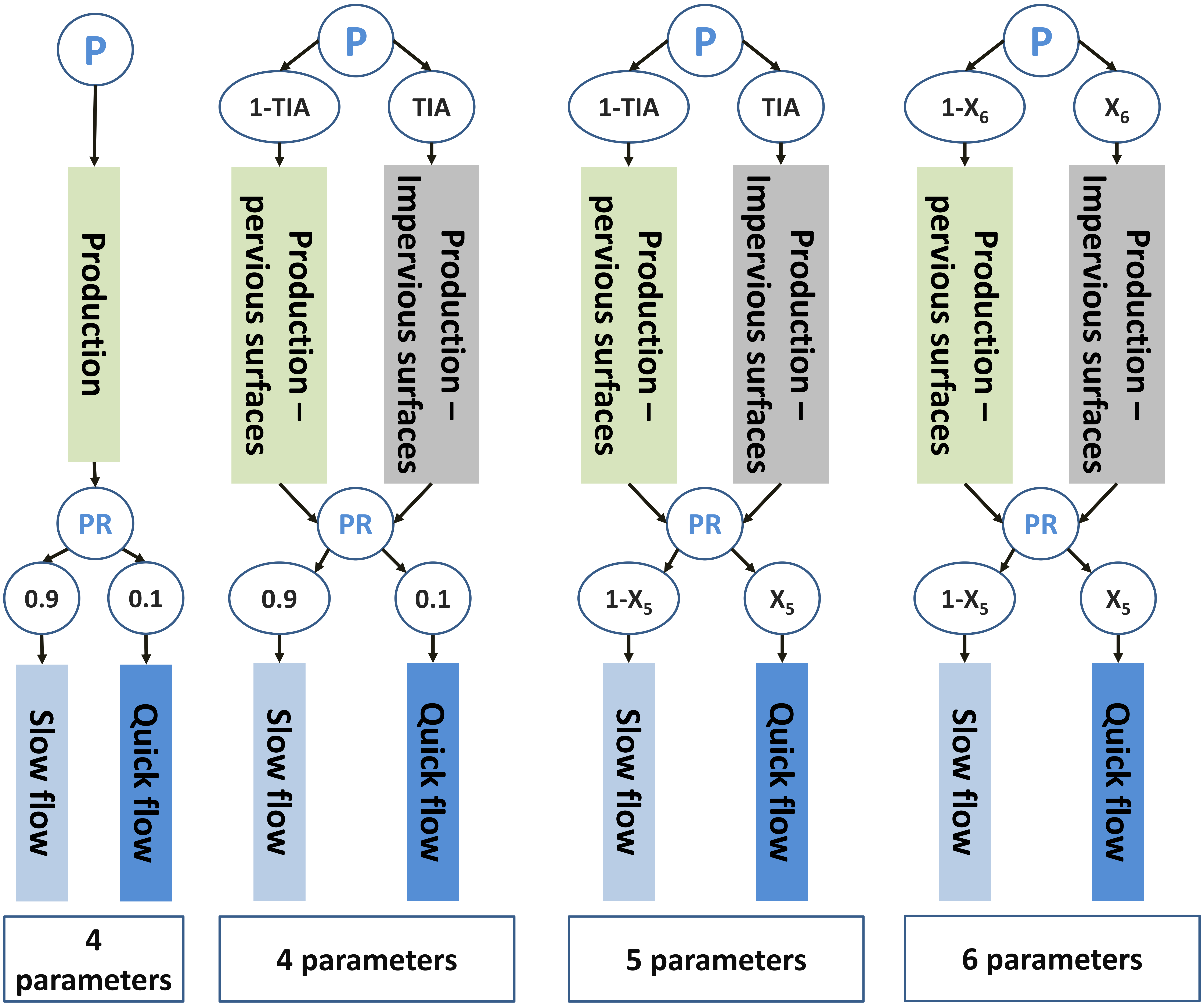
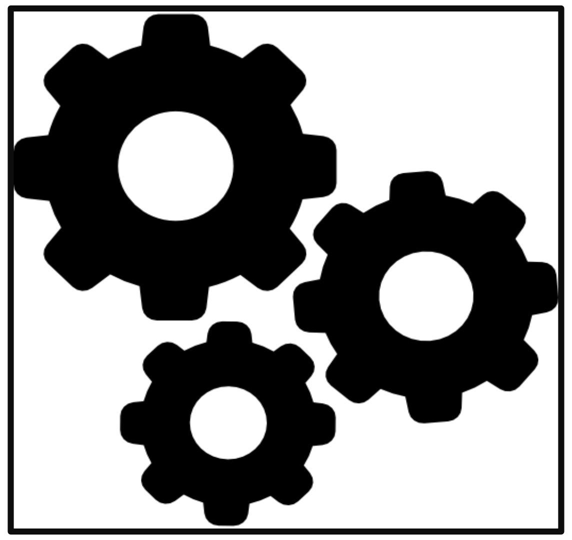


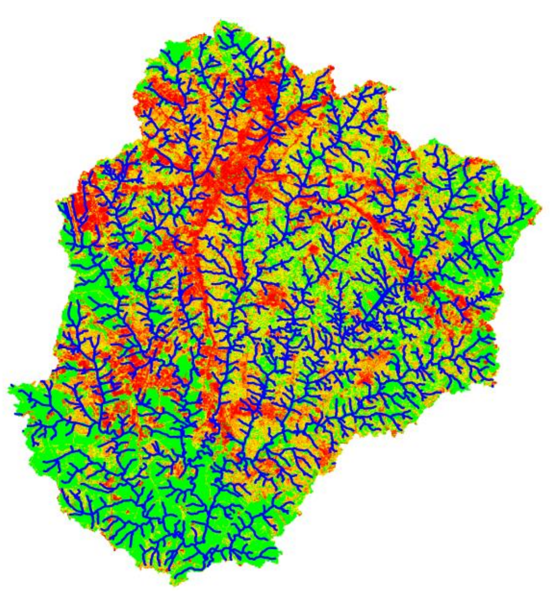
Tested modifications: number of calibrated parameters



Assessing the relevance of tested modifications



Test and evaluation



Year 1	...	Year N/2 - 1	Year N/2	Year N/2 + 1	...	Year N
P1				P2		

Calibration on P1 → **Test on P2 (continuous + events)**

Test on P1 (continuous + events) ← **Calibration on P2**

- **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 → r

Ratio of standard deviations → α

Ratio of means → β

Assessing the relevance of tested modifications

Type of assessment criterion	Criterion	Abbreviation	Ideal value
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	ε_{Qp}	**1**
	Error in event runoff volume	**VE**	**1**

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

$$\varepsilon_{Qp} = 1 - \frac{|Q_{sim}^p - Q_{obs}^p|}{Q_{obs}^p}$$

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

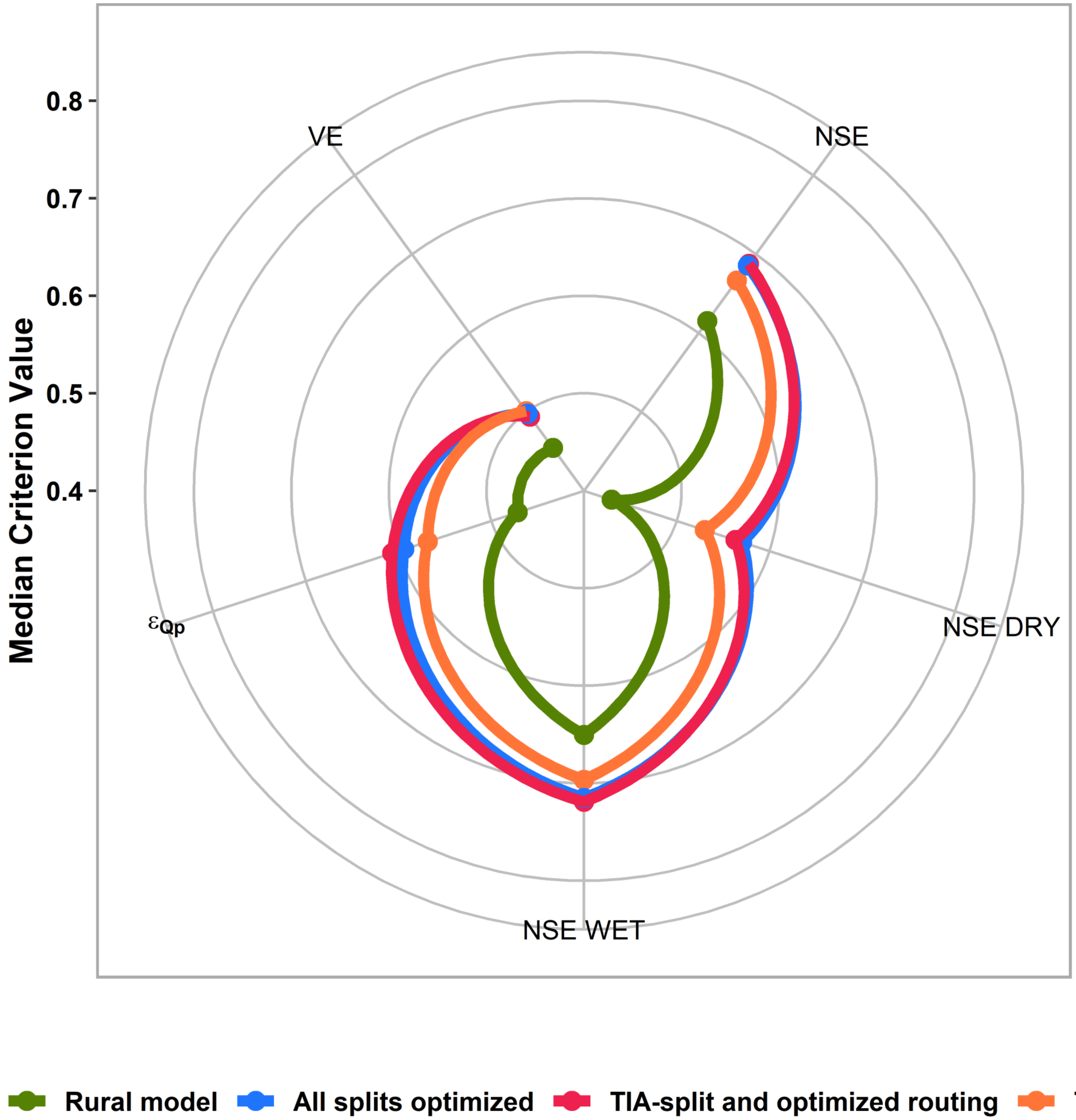
sim: simulated, **obs**: observed, Q^h: discharge at hour h, Q^p: peakflow

Calibration performances

Structure	Number of parameters	Median KGESQ (square root values)	Median KGE (non-transformed values)
Rural model	4	0.88	0.85
TIA-split	4	0.89	0.87
TIA-split and optimized routing	5	0.89	0.88
All splits optimized	6	0.90	0.88

More degrees of freedom (i.e., calibrated parameters) results in better calibration performances
Improved calibration by uniquely adding information from TIA

Test performances (using KGESQ-calibrated parameters)



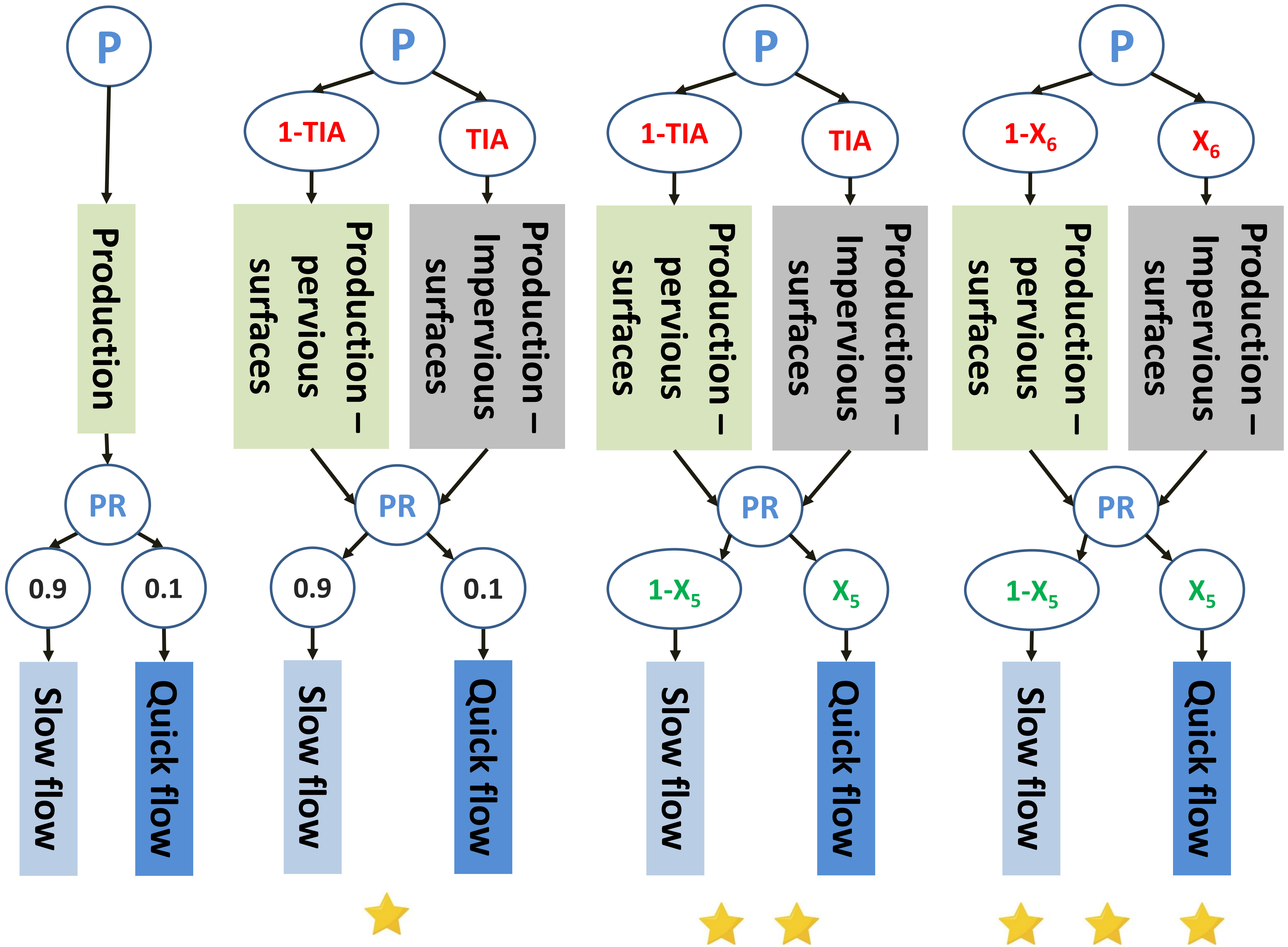
Adding an impervious branch results in better NSE performances, especially when focus is put on dry conditions

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

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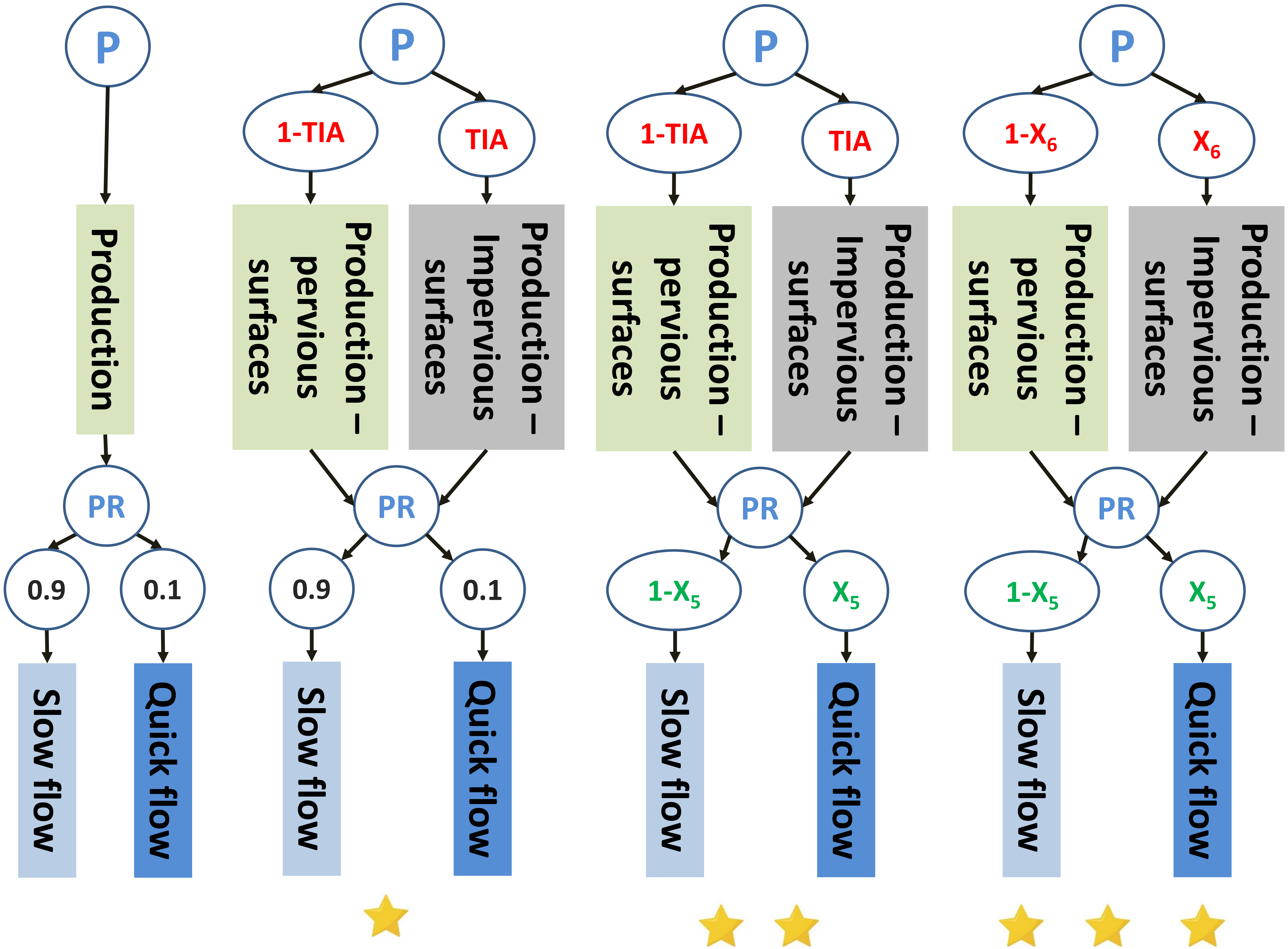

When the split parameters are set free, regionalization is needed to use the urbanized model for future scenarios prediction

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