**Supplementary information**

**Evaluation of rainfall–runoff model performance under non-stationary hydroclimatic conditions**

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**Contents**

Hydro-meteorological and catchment characteristics data (Tables S1 and S2); rainfall–runoff model calibration parameters for all thee models and periods at the two catchments (Tables S3–S8); percentage deviation in the percentile flow simulated by the models (Table S9–S14); and soil characteristics of the study catchments (Figure S1 and Table S15).

Schematic of IHACRES model (Figure S2); temporal changes in LAI at the two catchments (Figures S3 and S4); scatter plot of rainfall data with zero as missing values *vs* AWAP infilled data (Figure S5).

FDC of all thee model calibration (Dry1) and validation (Average2, Dry2 and Wet2) at catchment 410044 with missing rainfall data infilled with AWAP data (Figure S6)

Model calibration parameters for the Dry1 period at catchment 410044 with missing rainfall values replaced by the AWAP dataset (Table S16).

Equations to calculate performance indicators: NSE (Eq. (S1)), RMSE (Eq. (S2)) and PBIAS (Eq. (S3)).

**Table S1** Hydro-meteorological data used in this study.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Data | Catchment | Duration | Frequency | Source |
| Runoff | 405251 | 1974–2013 | Daily | Bureau of Meteorology (BoM), Water data repository |
| 410044 | 1941–2015 |
| Rainfall | 405251 | 1974–2013 | Daily | BoM, Climate data repository |
| 410044 | 1941–2015 |
| Maximum temperature | 405251 | 1974–2013 | Daily |
| 410044 | 1941–2015 |
| Minimum temperature | 405251 | 1974–2013 | Daily |
| 410044 | 1941–2015 |

**Table S2** Catchment characteristic data used in this study.

|  |  |  |  |
| --- | --- | --- | --- |
| Data | Catchment | Resolution (m) | Source |
| Digital elevation model (DEM) | 405251 | 25 × 25 | Department of Environment, Land, Water and Planning, Victoria Government |
| 410044 | Geoscience Australia, Elevation Information System |
| Land use / land cover | 405251 | 25 × 25 | Department of Economic Development, Jobs, Transport and Resources, Victoria Government |
| 410044 | Department of Environment and Climate Change, NSW Government |
| Soil map | 405251 | 25 × 25 | Victoria’s open data directory |
| 410044 | NSW Office of Environment and Heritage |
| Leaf area index (LAI) | 405251 | 55,570 × 55,570 (original)  900 × 900 (resampled) | Bi-monthly reanalysis dataset (ERA‑20CM) from ECMWF (1941-2010) and Integrated Climate Data Centre, University of Hamburg, Germany (2011-2015) |
| 410044 |

**Table S3** Calibrated model parameters for the Average1 calibration period at catchment 405251.

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Parameter | Unit | Calibrated value |
| IHACRES | τq | Day | 4.9 |
| τs | Day | 144.8 |
| *v*s | (-) | 0.44 |
| *d* | mm | 8.2 |
| *e* | (-) | 1 |
| *f* | (-) | 1.2 |
| HEC-HMS | CN | (-) | 85.2 |
| *Ip* | % | 2.1 |
| *Ia* | mm | 5.6 |
| *Lt* | min | 174.2 |
| K | h | 0.6 |
| x | (-) | 0.1 |
| SWATgrid | GWQMN | mm | 2875 |
| SOL\_AWC | mm mm-1 | 0.43 |
| ALPHA\_BF | day-1 | 0.74 |
| SOL\_K | mm h-1 | 0.09 |
| CN2 | (-) | 81 |
| ESCO | (-) | 0.08 |

**Table S4** Calibrated model parameters for the Dry1 calibration period at catchment 405251.

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Parameter | Unit | Calibrated value |
| IHACRES | τq | Day | 2.2 |
| τs | Day | 298.5 |
| *v*s | (-) | 0.85 |
| *d* | mm | 13.6 |
| *e* | (-) | 1 |
| *f* | (-) | 2.6 |
| HEC-HMS | CN | (-) | 88.3 |
| *Ip* | % | 2.6 |
| *Ia* | mm | 11.1 |
| *Lt* | min | 195.3 |
| K | h | 1.2 |
| x | (-) | 0.2 |
| SWATgrid | GWQMN | mm | 4250 |
| SOL\_AWC | mm mm-1 | 0.87 |
| ALPHA\_BF | day-1 | 0.44 |
| SOL\_K | mm h-1 | 0.08 |
| CN2 | (-) | 84 |
| ESCO | (-) | 0.06 |

**Table S5** Calibrated model parameters for the Wet1 calibration period at catchment 405251.

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Parameter | Unit | Calibrated value |
| IHACRES | τq | Day | 8.9 |
| τs | Day | 133.2 |
| *v*s | (-) | 0.36 |
| *d* | mm | 6.8 |
| *e* | (-) | 1 |
| *f* | (-) | 0.3 |
| HEC-HMS | CN | (-) | 83.2 |
| *Ip* | % | 2.0 |
| *Ia* | mm | 2.9 |
| *Lt* | min | 155.6 |
| K | h | 0.4 |
| x | (-) | 0.2 |
| SWATgrid | GWQMN | mm | 1885 |
| SOL\_AWC | mm mm-1 | 0.74 |
| ALPHA\_BF | day-1 | 0.77 |
| SOL\_K | mm h-1 | 0.12 |
| CN2 | (-) | 82.1 |
| ESCO | (-) | 0.07 |

**Table S6** Calibrated model parameters for the Average1 calibration period at catchment 410044.

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Parameter | Unit | Calibrated value |
| IHACRES | τq | Day | 6.2 |
| τs | Day | 169.6 |
| *v*s | (-) | 0.39 |
| *d* | mm | 5.2 |
| *e* | (-) | 1 |
| *f* | (-) | 1.7 |
| HEC-HMS | CN | (-) | 75.2 |
| *Ip* | % | 1.6 |
| *Ia* | mm | 5.1 |
| *Lt* | min | 552.3 |
| K | h | 1.5 |
| x | (-) | 0.3 |
| SWATgrid | GWQMN | mm | 4550 |
| SOL\_AWC | mm mm-1 | 0.81 |
| ALPHA\_BF | day-1 | 0.76 |
| SOL\_K | mm h-1 | 0.10 |
| CN2 | (-) | 73.6 |
| ESCO | (-) | 0.05 |

**Table S7** Calibrated model parameters for the Dry1 calibration period at catchment 410044.

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Parameter | Unit | Calibrated value |
| IHACRES | τq | Day | 3.2 |
| τs | Day | 302.2 |
| *v*s | (-) | 0.76 |
| *d* | mm | 11.6 |
| *e* | (-) | 1 |
| *f* | (-) | 2.4 |
| HEC-HMS | CN | (-) | 76.3 |
| *Ip* | % | 1.2 |
| *Ia* | mm | 8.9 |
| *Lt* | min | 635.2 |
| K | h | 1.9 |
| x | (-) | 0.4 |
| SWATgrid | GWQMN | mm | 4850 |
| SOL\_AWC | mm mm-1 | 0.88 |
| ALPHA\_BF | day-1 | 0.46 |
| SOL\_K | mm h-1 | 0.13 |
| CN2 | (-) | 74.2 |
| ESCO | (-) | 0.06 |

**Table S8** Calibrated model parameters for the Wet1 calibration period at catchment 410044.

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Parameter | Unit | Calibrated value |
| IHACRES | τq | Day | 9.3 |
| τs | Day | 29.3 |
| *v*s | (-) | 0.29 |
| *d* | mm | 3.9 |
| *e* | (-) | 1 |
| *f* | (-) | 0.9 |
| HEC-HMS | CN | (-) | 77.1 |
| *Ip* | % | 1.9 |
| *Ia* | mm | 3.5 |
| *Lt* | min | 489.5 |
| K | h | 1.3 |
| x | (-) | 0.2 |
| SWATgrid | GWQMN | mm | 1126 |
| SOL\_AWC | mm mm-1 | 0.41 |
| ALPHA\_BF | day-1 | 0.75 |
| SOL\_K | mm h-1 | 0.11 |
| CN2 | (-) | 76.3 |
| ESCO | (-) | 0.07 |

**Table S9** Percentage deviation in the percentile flow simulated by the models (relative to observed runoff) during Average1 calibration period at catchment 405251.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Percentile flow | Observed (m3/s) | IHACRES (% difference) | HEC-HMS (% difference) | SWATgrid (% difference) |
| Calibration (Average1) | | | | |
| 10% | 0.707 | 6.65 | -0.56 | -2.26 |
| 90% | 0.093 | -78.49 | -80.64 | -63.15 |
| Validation (Average2) | | | | |
| 10% | 0.881 | 36.32 | 35.98 | 18.27 |
| 90% | 0.086 | 5.08×102 | -37.21 | -1.16 |
| Validation (Dry2) | | | | |
| 10% | 0.264 | 48.48 | 26.89 | 6.44 |
| 90% | 1.0×10-5 | 2.89×102 | 2.29×102 | 7.99×104 |
| Validation (Wet2) | | | | |
| 10% | 1.344 | -12.05 | -12.35 | -5.36 |
| 90% | 0.135 | -62.96 | -55.56 | -19.26 |

**Table S10** Percentage deviation in the percentile flow simulated by the models (relative to observed runoff) during Dry1 calibration period at catchment 405251.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Percentile flow | Observed (m3/s) | IHACRES (% difference) | HEC-HMS (% difference) | SWATgrid (% difference) |
| Calibration (Dry1) | | | | |
| 10% | 0.513 | 19.10 | -3.51 | 9.36 |
| 90% | 0.025 | -88.00 | -40.00 | -24.00 |
| Validation (Average2) | | | | |
| 10% | 0.881 | 45.63 | -20.77 | 23.27 |
| 90% | 0.086 | -97.67 | -98.84 | -46.51 |
| Validation (Dry2) | | | | |
| 10% | 0.264 | -2.27 | 5.30 | 1.89 |
| 90% | 1.0×10-5 | 1.80×105 | 1.40×105 | 5.99×104 |
| Validation (Wet2) | | | | |
| 10% | 1.344 | -5.35 | -0.15 | -2.75 |
| 90% | 0.135 | -0.10 | -11.85 | -2.22 |

**Table S11** Percentage deviation in the percentile flow simulated by the models (relative to observed runoff) during Wet1 calibration period at catchment 405251.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Percentile flow | Observed (m3/s) | IHACRES (% difference) | HEC-HMS (% difference) | SWATgrid (% difference) |
| Calibration (Wet1) | | | | |
| 10% | 1.330 | 11.05 | 10.60 | 9.92 |
| 90% | 0.132 | 6.06 | -25.00 | 7.57 |
| Validation (Average2) | | | | |
| 10% | 0.881 | 5.40 | 59.14 | 25.08 |
| 90% | 0.086 | -8.14 | 89.53 | -13.95 |
| Validation (Dry2) | | | | |
| 10% | 0.264 | 1.23×102 | 1.18×102 | 61.74 |
| 90% | 1.0×10-5 | 3.89×105 | 6.99×105 | 2.79×105 |
| Validation (Wet2) | | | | |
| 10% | 1.344 | 6.77 | 4.68 | 1.64 |
| 90% | 0.135 | 6.67 | 16.29 | 8.89 |

**Table S12** Percentage deviation in the percentile flow simulated by the models (relative to observed runoff) during Average1 calibration period at catchment 410044.

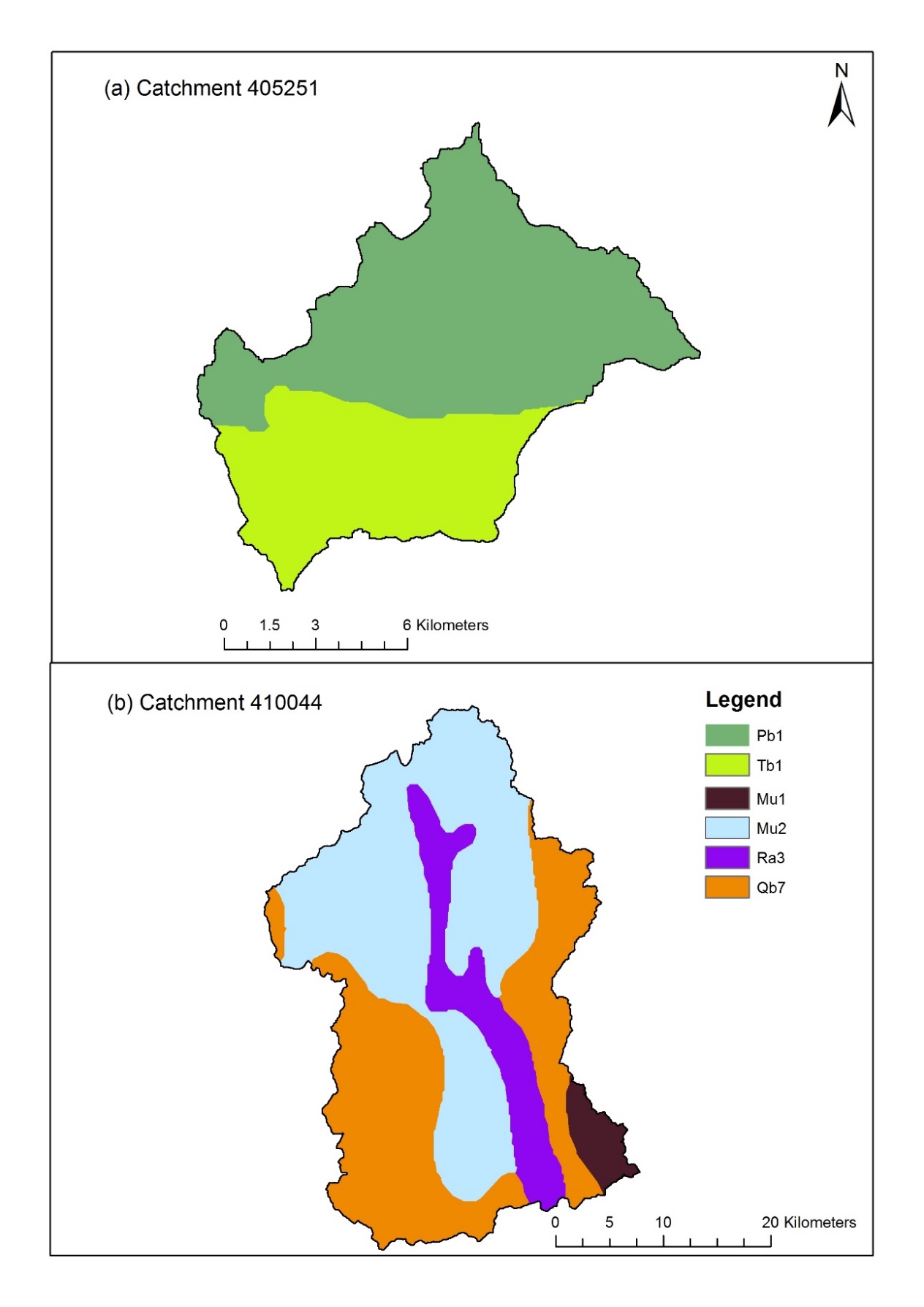
|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Percentile flow | Observed (m3/s) | IHACRES (% difference) | HEC-HMS (% difference) | SWATgrid (% difference) |
| Calibration (Average1) | | | | |
| 10% | 1.764 | 81.18 | 84.69 | 33.50 |
| 90% | 0.017 | 1.33×103 | 1.49×103 | 1.59×102 |
| Validation (Average2) | | | | |
| 10% | 3.394 | 33.35 | 30.26 | 25.98 |
| 90% | 0.009 | 5.41×103 | 5.22×103 | 1.56×102 |
| Validation (Dry2) | | | | |
| 10% | 0.308 | 6.35×102 | 6.37×102 | 3.23×102 |
| 90% | 0.002 | 1.65×104 | 1.73×104 | 8.85×103 |
| Validation (Wet2) | | | | |
| 10% | 3.211 | 55.71 | 29.74 | 31.39 |
| 90% | 0.052 | 1.00×103 | 1.02×103 | 6.04×102 |

**Table S13** Percentage deviation in the percentile flow simulated by the models (relative to observed runoff) during Dry1 calibration period at catchment 410044.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Percentile flow | Observed (m3/s) | IHACRES (% difference) | HEC-HMS (% difference) | SWATgrid (% difference) |
| Calibration (Dry1) | | | | |
| 10% | 1.771 | -80.52 | -68.15 | -38.85 |
| 90% | 0.011 | -99.91 | 36.33 | 37.23 |
| Validation (Average2) | | | | |
| 10% | 3.394 | -33.44 | -9.48 | -25.34 |
| 90% | 0.009 | -99.89 | 6.82×102 | 11.00 |
| Validation (Dry2) | | | | |
| 10% | 0.308 | 2.37×102 | 3.57×102 | 61.68 |
| 90% | 0.002 | -99.5 | 2.15×103 | 1.00×102 |
| Validation (Wet2) | | | | |
| 10% | 3.211 | -33.76 | -8.93 | -53.00 |
| 90% | 0.052 | -99.60 | -88.81 | -58.11 |

**Table S14** Percentage deviation in the percentile flow simulated by the models (relative to observed runoff) during Wet1 calibration period at catchment 410044.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Percentile flow | Observed (m3/s) | IHACRES (% difference) | HEC-HMS (% difference) | SWATgrid (% difference) |
| Calibration (Wet1) | | | | |
| 10% | 2.076 | 44.94 | 41.43 | 28.98 |
| 90% | 0.003 | -99.67 | -98.52 | -66.67 |
| Validation (Average2) | | | | |
| 10% | 3.394 | -6.36 | -8.34 | -8.75 |
| 90% | 0.009 | -99.88 | -97.45 | 3.88×102 |
| Validation (Dry2) | | | | |
| 10% | 0.308 | 50.65 | 80.19 | 59.74 |
| 90% | 0.002 | -99.87 | -97.96 | 5.50×102 |
| Validation (Wet2) | | | | |
| 10% | 3.211 | -5.26 | -3.22 | -9.12 |
| 90% | 0.052 | -99.85 | -98.58 | 23.08 |



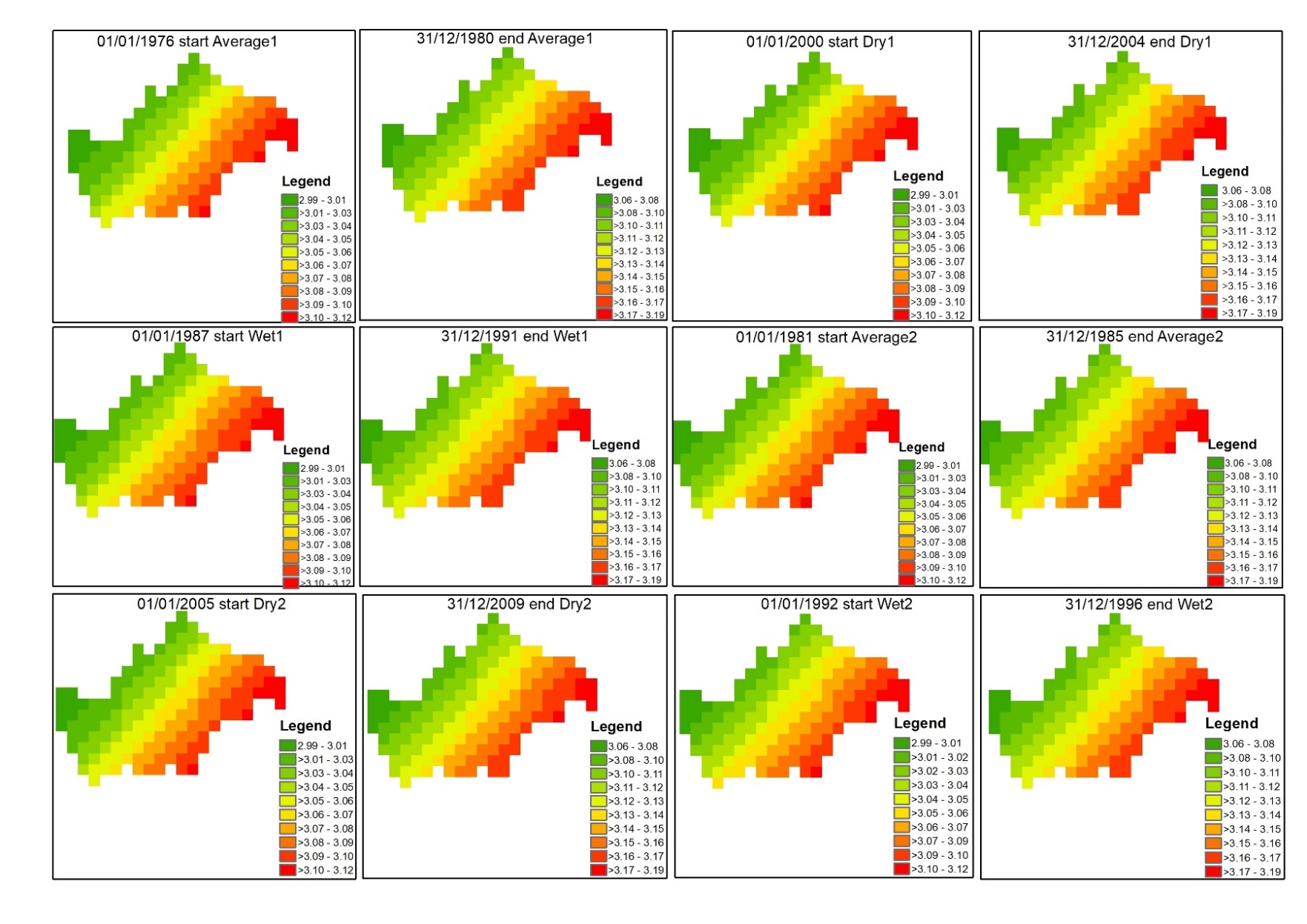
**Figure S1** The Factual Key soil classification for catchments (a) 405251 and (b) 410044.

**Table S15** Hydrological soil properties of the Factual Key soil classification at the catchments.

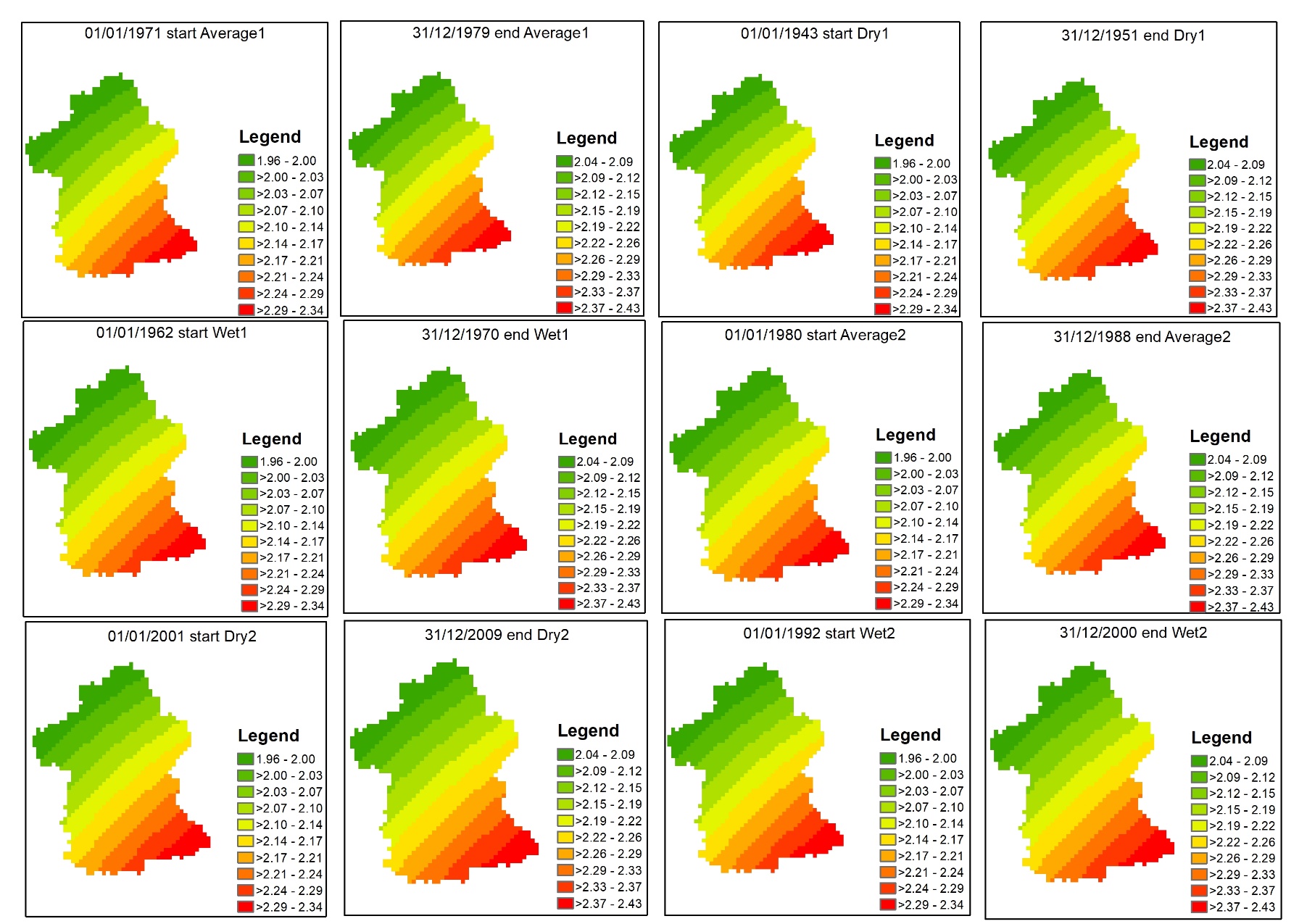
|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Code | Horizon | SDEPTH | WHC | THICK | KSAT | SAT | FC | WP | PAW |
| Pb1 | A | 0.90 | 93 | 0.30 | 100 | 0.42 | 0.27 | 0.13 | 44 |
| B | 0.60 | 30 | 0.40 | 0.36 | 0.28 | 57 |
| Tb1 | A | 0.90 | 60 | 0.30 | 30 | 0.38 | 0.23 | 0.09 | 39 |
| B | 0.60 | 10 | 0.34 | 0.34 | 0.30 | 21 |
| Mu1 | A | 1.00 | 116 | 0.30 | 100 | 0.42 | 0.23 | 0.09 | 41 |
| B | 0.70 | 100 | 0.37 | 0.31 | 0.21 | 74 |
| Mu2 | A | 1.10 | 114 | 0.30 | 100 | 0.43 | 0.24 | 0.10 | 39 |
| B | 0.80 | 30 | 0.39 | 0.30 | 0.19 | 76 |
| Ra3 | A | 0.80 | 68 | 0.30 | 30 | 0.42 | 0.24 | 0.10 | 38 |
| B | 0.50 | 10 | 0.37 | 0.37 | 0.30 | 30 |
| Qb7 | A | 0.80 | 66 | 0.30 | 100 | 0.40 | 0.25 | 0.11 | 34 |
| B | 0.50 | 30 | 0.36 | 0.36 | 0.30 | 35 |

SDEPTH: weighted average soil depth in m; WHC: weighted average plant available water holding capacity in mm; THICK: weighted average thickness in m; KSAT: weighted average of median saturated hydraulic conductivity in mm/h; SAT: average weighted saturated volumetric water content in m3/m3; FC: average values of volumetric water content at 0.1 bar suction (field capacity) in m3/m3; WP: average values of volumetric water content at 15 bar suction (wilting point) in m3/m3; PAW: plant available water in mm.

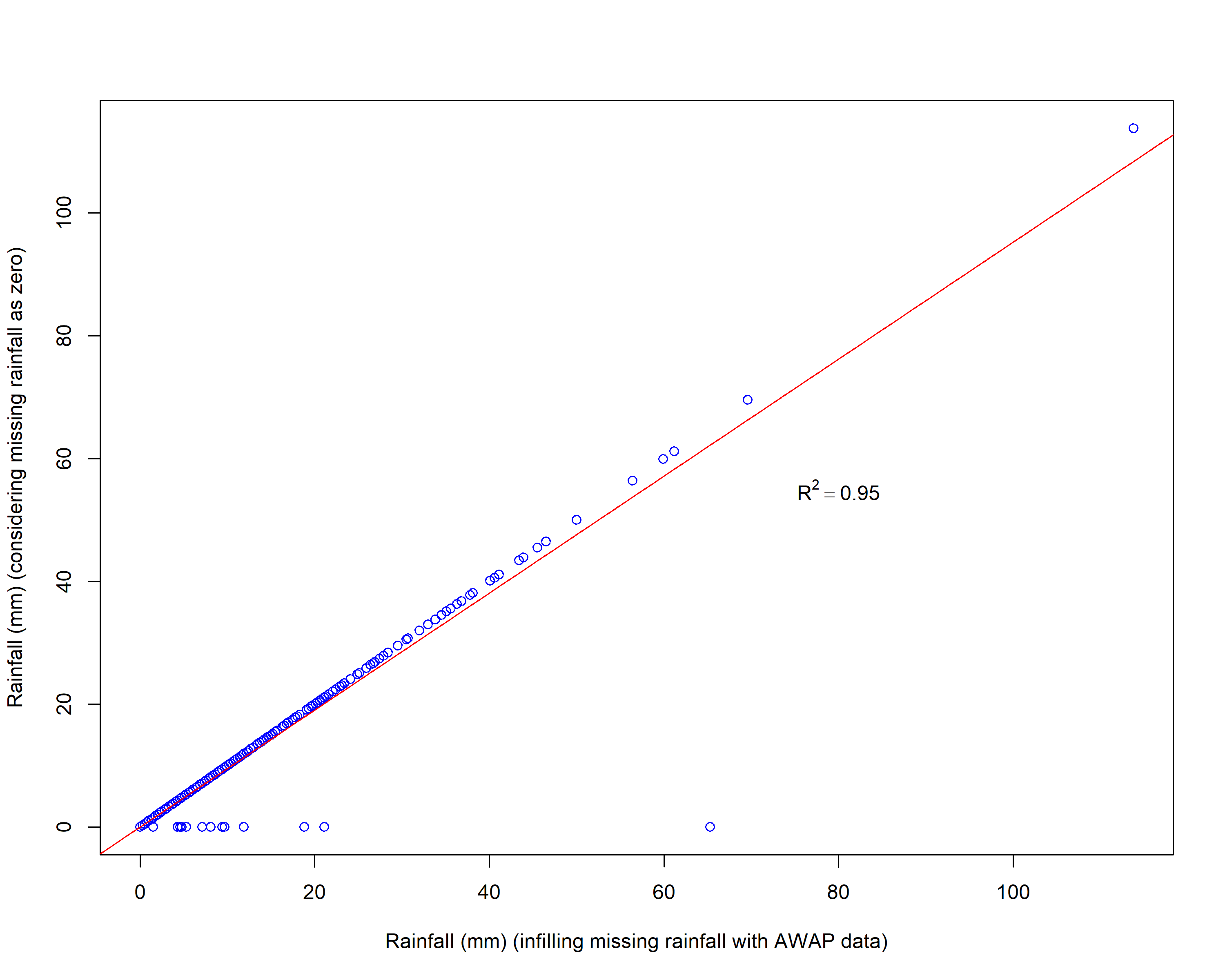
|  |
| --- |
| G:\PhD_files\Articles\Paper2\Figures\Fig_2_IHACRES_model_structure.png |
| **Figure S2** Schematic of the IHACRES model. Adapted from Tegegne *et al*. (2017). |



**Figure S3** Temporal changes in LAI data for different calibration and validation periods at catchment 405251.



**Figure S4** Temporal changes in LAI data for different calibration and validation periods at catchment 410044.



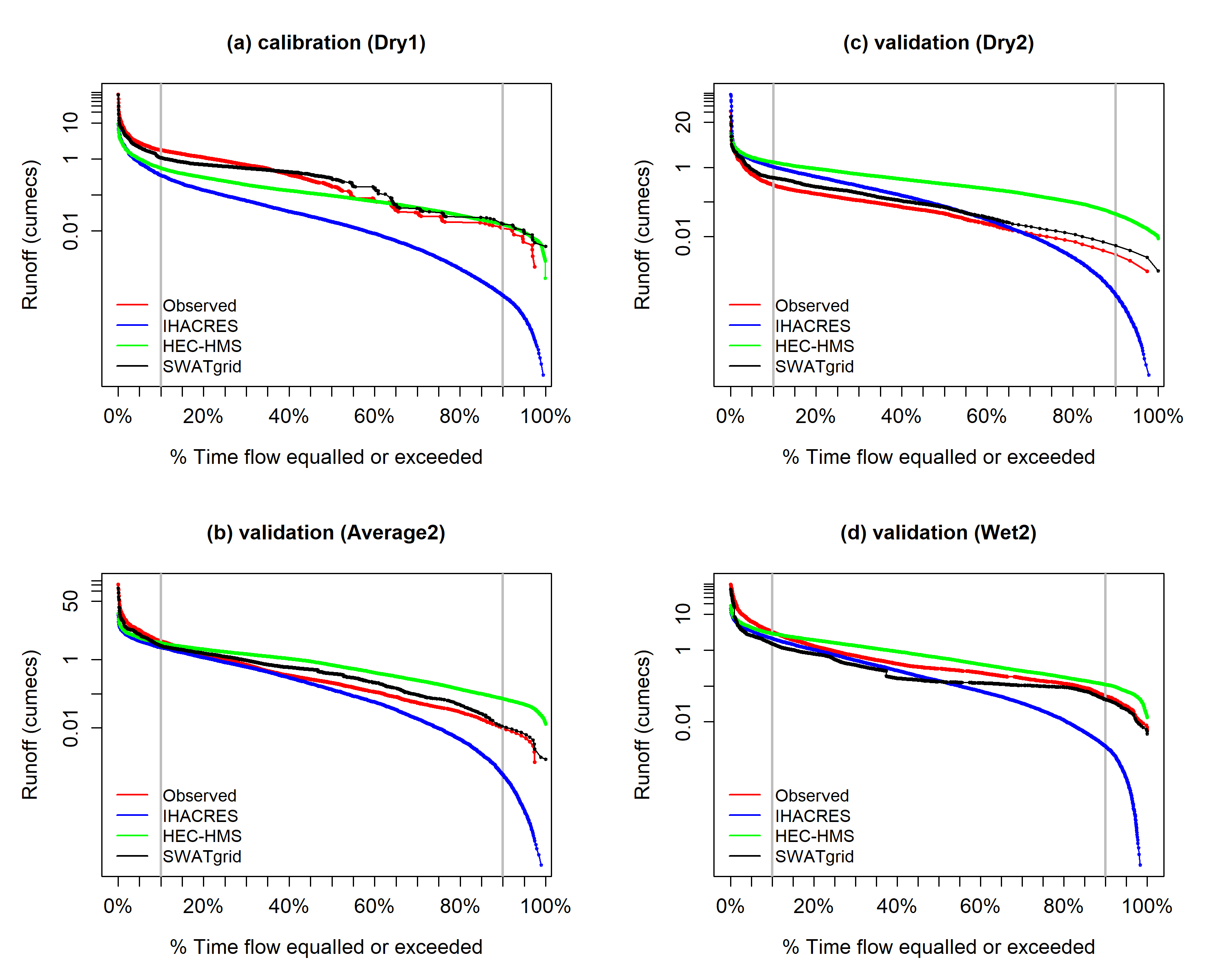
**Figure S5** Scatter plot of AWAP infilled missing data vs missing data considered as zero rainfall at the station 73022 for catchment 410044.

(S1)

(S2)

(S3)

where is the observed runoff at *i*th time step, is the simulated runoff at the *i*th time step and is the mean observed runoff for the whole time period considered.



**Figure S6** FDC for model simulation during (a) calibration (Dry1), (b) validation (Average2), (c) validation (Dry2) and (d) validation (Wet2) in case of catchment 410044 while considering missing rainfall replaced by Australian Water Availability Project (AWAP) dataset (vertical grey lines indicate the division of 10% and 90% flows).

**Table S16** Calibrated model parameters for the Dry1 calibration period at catchment 410044 with missing rainfall values replaced by the AWAP dataset.

|  |  |  |  |
| --- | --- | --- | --- |
| Model | Parameter | Unit | Calibrated value |
| IHACRES | τq | Day | 3.6 |
| τs | Day | 311.6 |
| *v*s | (-) | 0.77 |
| *d* | mm | 12.4 |
| *e* | (-) | 1.1 |
| *f* | (-) | 1.9 |
| HEC-HMS | CN | (-) | 78 |
| *Ip* | % | 1.5 |
| *Ia* | mm | 8.8 |
| *Lt* | min | 633.9 |
| K | h | 1.75 |
| x | (-) | 0.3 |
| SWATgrid | GWQMN | mm | 4822 |
| SOL\_AWC | mm mm-1 | 0.86 |
| ALPHA\_BF | day-1 | 0.45 |
| SOL\_K | mm h-1 | 0.15 |
| CN2 | (-) | 77 |
| ESCO | (-) | 0.07 |