4dHydro Tier 1 LSM/HM community reference outputs user manual

# Introduction

The LSM/HM community reference outputs are a set of hydrological simulation outputs, from previous studies, of various land-surface and hydrological models. These outputs represent the current state-of-the-art in hydrological modeling (i.e. before the improvements made in the 4dHydro project) and are used as a baseline reference for the rest of the project. All model outputs can be found at [4DHydro's Open Science Catalog](https://opensciencedata.4dhydro.eu/).

The hydrological simulations themselves consists of various different models, weather/climate forcings, spatial resolutions, periods and variables. A full description for all models, including references is given in *Section 1* and a full description for each hydrological simulation is given in *Section 2*.

Although the hydrological simulations are not harmonized, the LSM/HM community reference outputs were harmonized following our developed storage protocol. The storage protocol details all the possible output variables (e.g. discharge, evapotranspiration and total water storage), regions (Europe, Rhine, Po and Tugela) and file formatting in *Section 3*.

# Model descriptions

The following models participated in the project: Community Land Model (CLM), PCRaster GLOBal Water Balance model (PCR-GLOBWB), wflow-sbm, ParFlow-CLM, GEOframe and TETIS. A description and references for each model are given below.

## Community Land Model (3.5)

### Primary reference

Oleson, K. W. et al. Improvements to the Community Land Model and their impact on the hydrological cycle. J. Geophys. Res-Biogeo. 113, G01021 (2008).

### Secondary references

Naz, B.S., Kollet, S., Franssen, HJ.H. et al. A 3 km spatially and temporally consistent European daily soil moisture reanalysis from 2000 to 2015. Sci Data 7, 111 (2020). https://doi.org/10.1038/s41597-020-0450-6

### Included modules

Energy balance hydrology, snow, rivers, and vegetation.

### Source code

https://www.cgd.ucar.edu/tss/clm/distribution/clm3.5/index.html

### Other

https://github.com/HPSCTerrSys/CLM3.5/tree/tsmp-patches/src

## PCR-GLOBWB (v2.0)

### Primary reference

Sutanudjaja, E. H., van Beek, R., Wanders, N., Wada, Y., Bosmans, J. H., Drost, N., ... & Bierkens, M. F. (2018). PCR-GLOBWB 2: a 5 arcmin global hydrological and water resources model. Geoscientific Model Development, 11(6), 2429-2453. DOI: 10.5194/gmd-11-2429-2018

### Secondary references

van Beek, L. P. H., & Bierkens, M. F. P. (2009). The global hydrological model PCR-GLOBWB: conceptualization, parameterization and verification. Utrecht University, Utrecht, The Netherlands, 1, 25-26. http://vanbeek.geo.uu.nl/suppinfo/vanbeekbierkens2009.pdf.

van Beek, L. P. H., Wada, Y., & Bierkens, M. F. (2011). Global monthly water stress: 1. Water balance and water availability. Water Resources Research, 47(7), W07517. DOI: 10.1029/2010WR009791.

Wada, Y., van Beek, L. P. H., Viviroli, D., Dürr, H. H., Weingartner, R., & Bierkens, M. F. (2011). Global monthly water stress: 2. Water demand and severity of water stress. Water Resources Research, 47(7). DOI: 10.1029/2010WR009792

### Included modules

Water withdrawal & consumption, lakes, reservoir operation

### Source code

https://github.com/UU-Hydro/PCR-GLOBWB\_model/tree/master

### Other

https://pcrglobwb.readthedocs.io/en/latest/

## Wflow\_sbm (v0.7.1)

### Primary reference

van Verseveld, W. J., Weerts, A. H., Visser, M., Buitink, J., Imhoff, R. O., Boisgontier, H., Bouaziz, L., Eilander, D., Hegnauer, M., ten Velden, C., and Russell, B. (2022). Wflow\_sbm v0.6.1, a spatially distributed hydrologic model: from global data to local applications. Geoscientific Model Development Discussions. https://doi.org/10.5194/gmd-2022-182, in review.

### Secondary references

Imhoff, R. O., van Verseveld, W. J., van Osnabrugge, B., & Weerts, A. H. (2020). Scaling point-scale (pedo) transfer functions to seamless large-domain parameter estimates for

high-resolution distributed hydrologic modeling: An example for the Rhine River. Water Resources Research, 56, e2019WR026807. https://doi.org/10.1029/2019WR026807

Eilander, D., van Verseveld, W., Yamazaki, D., Weerts, A., Winsemius, H. C., and Ward, P. J. (2021). A hydrography upscaling method for scale-invariant parametrization of distributed hydrological models. Hydrology and Earth System Sciences, 25, 5287–5313, https://doi.org/10.5194/hess-25-5287-2021

Eilander, D., Boisgontier, H., Bouaziz, L. J. E., Buitink, J., Couasnon A., Dalmijn, B., Hegnauer, M., de Jong, T., Loos, S., Marth, I., van Verseveld, W. (2023). HydroMT: Automated and reproducible model building and analysis. Journal of Open Source Software, 8(83), 4897. https://doi.org/10.21105/joss.04897

### Included modules

Lakes, reservoir operation, glaciers, 1d floodplain schematization in local inertial routing module.

### Source code

https://github.com/Deltares/Wflow.jl

### Other

https://deltares.github.io/Wflow.jl/dev/

https://deltares.github.io/hydromt\_wflow/latest/

## GEOframe modelling system

### Primary reference

Formetta G., Antonello A., Franceschi S., David O., and Rigon R., Hydrological modelling with components: A GIS-based open-source framework, Environmental Modelling & Software, 5 (2014), 190-200

Rigon, Formetta, Bancheri, Tubini, D’Amato, David, and Massari. n.d. “HESS Opinions: Participatory Digital eARth Twin Hydrology Systems (DARTHs) for Everyone – a Blueprint for Hydrologists.” Hydrology and Earth System Sciences. https://doi.org/10.5194/hess-26-4773-2022.

### Secondary references

Formetta, G.; Mantilla, R.; Franceschi, S., Antonello A., Rigon R., The JGrass- NewAge system for forecasting and managing the hydrological budgets at the basin scale: models of flow generation and propagation/routing, Geoscientific Model Development Volume: 4 Issue: 4 Pages: 943-955, DOI: 10.5194/gmd-4- 943-201, 2011.

Abera, W., A. Antonello, S. Franceschi, and G. Formetta. 2014. “The uDig Spatial Toolbox for Hydro-Geomorphic Analysis.” In Geomorphological Techniques (Online Edition), edited by British Society for Geomorphology. British Society for Geomorphology.

Bancheri, M., A flexible approach to the estimation of water budgets and its connection to the travel time theory, Ph.S. Dissertation, 2017.

Bancheri, M., Serafin, F., & Rigon, R. (2019). The Representation of Hydrological Dynamical Systems Using Extended Petri Nets (EPN). Water Resources Research, 8(01), 159–27. http://doi.org/10.1029/2019WR025099.

### Included modules

Catchment and Hydrologic Response Unit delineation (from The Horton Machine), Meteorological variables interpolation with Kriging techniques. Estimation of incident Radiation  with various decomposition models. Estimation of evapotranspiration (Priestley Taylor, Penman-FAO, Prospero models), Snow (degree day, Hock’s model, Cazorzi e Dalla Fontana model), Rainfall-Runoff modelling (reservoir type of models), Propagation (Muskingham-Cunge), Lake and Reservoirs models.

### Source code

https://github.com/geoframecomponents

### Others

http://geoframe.blogspot.it/

https://abouthydrology.blogspot.com/2022/03/geoframe-essentials.html

geoframe-components-users@googlegroups.com

## Mesoscale Hydrological Model (release\_5.11.2, commit 9ecb1875)

### Primary reference

Samaniego, L., Kumar, R. and Attinger, S., 2010. Multiscale parameter regionalization of a grid‐based hydrologic model at the mesoscale. Water Resources Research, 46(5).

### Secondary references

Kumar, R., Samaniego, L. and Attinger, S., 2013. Implications of distributed hydrologic model parameterization on water fluxes at multiple scales and locations. Water Resources Research, 49(1), pp.360-379.

Thober, S., Cuntz, M., Kelbling, M., Kumar, R., Mai, J. and Samaniego, L., 2019. The multiscale routing model mRM v1. 0: Simple river routing at resolutions from 1 to 50 km. Geoscientific Model Development, 12(6), pp.2501-2521.

Rakovec, O., Kumar, R., Mai, J., Cuntz, M., Thober, S., Zink, M., Attinger, S., Schäfer, D., Schrön, M. and Samaniego, L., 2016. Multiscale and multivariate evaluation of water fluxes and states over European river basins. Journal of Hydrometeorology, 17(1), pp.287-307.

### Included modules

Basic hydrologic modules: snow processes are based on the day-degree approach, soil moisture is processed based on the Feddes equation for ET reduction, multi-layer infiltration capacity approach (Brooks-Corey like); direct runoff is based on linear reservoir exceedance approach; PET is based on Hagreaves-Samani method; interflow is approximated by storage reservoir with one outflow threshold and nonlinear response; groundwater is assumed to be a linear reservoir; river routing is approximated by adaptive timestep, spatially varying celerity.

### Source code

https://git.ufz.de/mhm/mhm

Commit 9ecb1875

### Other

https://github.com/mhm-ufz

Luis Samaniego, Rohini Kumar, Matthias Zink, Matthias Cuntz, Juliane Mai, Stephan Thober, Christoph Schneider, Giovanni Dalmasso, Jude Musuuza, Oldrich Rakovec, John Craven, David Schäfer, Vladyslav Prykhodko, Martin Schrön, Diana Spieler, Johannes Brenner, Ben Langenberg, Lennart Schüler, Simon Stisen, Cüneyd M. Demirel, Miao Jing, Maren Kaluza, Robert Schweppe, Pallav Kumar Shrestha, Nicola Döring and Sebastian Müller (2023) “mhm-ufz/mHM: v5.13.1”, Zenodo [Online]. DOI: 10.5281/zenodo.8279545.

##  ParFlow/CLM (v3.8.0)

### Primary reference

Belleflamme et al., 2023: https://doi.org/10.3389/frwa.2023.1183642

### Secondary references

Kollet & Maxwell, 2006: https://doi.org/10.1016/j.advwatres.2005.08.006

Kuffour et al., 2020: https://doi.org/10.5194/gmd-13-1373-2020

Maxwell et al., 2015: https://doi.org/10.5194/gmd-8-923-2015

### Included modules

integrated 3D model covering variably saturated zone and groundwater, so no separate modules for the hydrological part

Module: Common Land Model (CLM) for interactions at the surface (energy and water exchange)

### Source code

GitHub: https://github.com/parflow

### Other

https://parflow.org/

https://adapter-projekt.de/wetter-produkte/vorhersagen-parflow-clm-deutschland-und-nachbargebiete.html (in German)

https://adapter-projekt.de/bulletin/index\_en.html

https://wasser-monitor.de/ (in German)

## TETIS-mHM (Version 1.0)

### Primary reference

S. Pool, F. Francés, A. Garcia-Prats, M. Pulido-Velázquez, C. Sanchis-Ibor, M. Schirmer, H. Yang and J. Jiménez-Martínez (2021). From Flood to Drip Irrigation Under Climate Change: Impacts on Evapotranspiration and Groundwater Recharge in the Mediterranean Region of Valencia (Spain). Earth’s Future, 9 (5), e2020EF001859.

C. Puertes, M. González-Sanchis, A. Lidón, I. Bautista, C. Llull, A.D. del Campo and F. Francés (2020). Improving the modelling and understanding of carbon-nitrogen-water interactions in a semiarid Mediterranean oak forest. Ecological Modelling, 420: 108976.

C. Echeverría, G. Ruiz-Pérez, C. Puertes, L. Samaniego, B. Barrett and F. Francés (2019). Assessment of Remotely Sensed Near-Surface Soil Moisture for Distributed Eco-Hydrological Model Implementation. Water, 11 (12): 2613.

G. Ruiz-Pérez, J. Koch, S. Manfreda, K. Caylor, and F. Francés, “Calibration of a parsimonious distributed ecohydrological daily model in a data-scarce basin by exclusively using the spatio-temporal variation of NDVI,” Hydrology and Earth System Sciences, vol. 21, no. 12, pp. 6235–6251, 2017. 4, 7, 24

G. Ruiz-Pérez, M. González-Sanchis, A.D. Del Campo and F. Francés (2016). Can a simple parsimonious model implemented with satellite data be used for modelling the vegetation dynamics and water cycle in water-controlled environments? Ecological Modelling, 324, 45–53.

G. Bussi, F. Francés, E. Horel, J.A., López-Tarazón and R. Batalla (2014). Modelling the impact of climate change on sediment yield in a highly erodible Mediterranean catchment. Journal of Soils and Sediments, 14 (12), 1921-1937.

Vélez, JJ, F. López Unzú, M. Puricelli and F. Francés (2009). Parameter extrapolation to ungauged basins with a hydrological distributed model in a regional framework. Hydrol. Earth Syst. Sci., 13, 229–246.

Francés, F. I. Vélez and J. Vélez (2007). Split-parameter structure for the automatic calibration of distributed hydrological models. Journal of Hydrology, 332, 226-240.

### Secondary references

J. Gomis-Cebolla, A. Garcia-Arias, M. Perpinyà-Vallès and F. Francés (2022). Evaluation of SENTINEL-1, SMAP and SMOS surface soil moisture products for distributed eco-hydrological modelling in Mediterranean forest basins. J. Hydrol., 608, 127569, 19 pp.

S. Siswanto and F. Francés (2019). How land use/land cover changes can affect water, flood and sediments in a tropical watershed: a case study using distributed modelling in Upper Citarum watershed, Indonesia. Environ. Earth Sci., 78 (17): 550.

V. Ruiz-Villanueva, M. Stoffel, G. Bussi, F. Francés and C. Bréthaut (2015). Climate change impacts on discharges of the Rhone River in Lyon by the end of the 21st century: model results and implications. Regional Environmental Change, 15 (3), 505-515.

### Included modules

### This version of TETIS retains its vertical conceptualization (version 9.1), while the horizontal one is that of the mHM model. TETIS includes submodules for reservoir operation, snow accumulation and melting, sediment erosion, transport and deposition, nitrogen cycle, natural dynamic vegetation, flood and drip irrigation, and crop production. Satellite information (any spatial observation of any state variable) can be included in a multiobjective calibration process, such as NDVI or surface soil moisture.

### Source code

http://lluvia.dihma.upv.es/ES/software/software.html

### Other

http://lluvia.dihma.upv.es/index\_es.html

# Simulation descriptions

Each model could supply various hydrological simulations for various regions. Below is a description for the hydrological simulations.

## Community Land Model at 3km with REA6

### Simulation options

* Period: 1995 - 2018
* Region: EURO-CORDEX domain
* Settings: default
* Spin up: 40 years

### Resolution

* Spatial resolution: 0.0275° (3 km)
* Temporal resolution: daily

### Input datasets

#### Meteorology (and pre-processing)

The COSMO-REA6 dataset at 6 km (Bollmeyer et al., 2015) resolution was re-gridded to 0.0275° (3 km) using the first-order conservative interpolation method.

#### Soil

FAO/UNESCO Digital Soil Map of the World

#### Vegetation

The land cover description comes from MODIS land cover (MCD12Q1 v5.1), vegetation continuous fields (MOD44B v5.1), LAI (MCD15A2 v5), and albedo (MCD43B3 v5) products (Lawrence and Chase, 2007)

#### Calibration

No model calibration was performed

### Output variables

ET: evapotranspiration (Total evapotranspiration flux, kg m-2 s-1)

SM: soil moisture (Volumetric soil moisture content, %)

Q: discharge (Discharge flux, m-3 s-1)

TWS: total water storage (Total water storage content, kg m-2)

## PCR-GLOBWB at 5 arc-minutes with ERA-Interim

### Simulation options

* Period: 1960 - 2015
* Region: global
* Settings: default, including human-impacts
* Spin up: based on a 150 years simulation with 1958-2000 climatology

### Resolution

* Spatial resolution: 5 arc-minutes
* Temporal resolution: daily

### Input datasets\*

\* See Sutanudjaja et al. (2018) for more information

#### Meteorology (and pre-processing)

Precipitation, temperature and reference potential evapotranspiration are based on ERA-Interim at a daily time step. Reference potential evapotranspiration was determined using the Penman-Monteith equation (Allen et al., 1998). Spatial downscaling was uniform for precipitation and reference evapotranspiration and laps-rate based for temperature.

#### Soil

Soil parameters are based on the Digital Soil Map of the World (DSMW) (FAO, 2007). Topography parameters are based on HydroSHEDS (Lehner et al., 2008) combined with 30 arcsec GTOPO30 (Gesch et al., 1999) and 1 km Hydro1k (USGS EROS Data Center, 2006).

#### Land cover

Land cover parameters are based on the Global Land Cover Characteristics (GLCC) dataset version 2.0 (Loveland et al., 2000) in combination with vegetation specific parameters (Hagemann et al., 1999; Hagemann, 2000). Irrigation land cover parameters (i.e. paddy and non-paddy), are based on the MIRCA2000 dataset (Portmann et al., 2010) and the Global Crop Water Model (Siebert and Döll, 2010).

#### Groundwater

Aquifer parameters are based on the GLobal HYdrogeology MaPS (GLHYMPS) dataset (Gleeson et al., 2014).

#### Water use

Irrigation area extent is are based on the MIRCA2000 dataset (Portmann et al., 2010). Lake and reservoirs parameters are based on the Global Lakes and Wetlands Database (GLWD) (Lehner and Döll, 2004) and the Global Reservoir and Dam Database (GRanD) (Lehner et al., 2011).

### Output variables

Discharge, actual evapotranspiration, soil moisture, total water storage

## Wflow\_sbm v0.7.1 Rhine at 30 arc-seconds with ERA5

### Simulation options

* Period: 1990 – 2022
* Region: Rhine River
* Settings: default HydroMT derivation (Eilander et al., 2023), 1D floodplain schematization with kinematic wave land and local-inertial river routing, glaciers, reservoirs and lakes.
* Spin up: 2 years with same dataset from 1988 up to 1990.

### Resolution

* Spatial resolution: 30 arc-seconds
* Temporal resolution: daily

### Input datasets

#### Meteorology (and pre-processing)

Daily precipitation, temperature and reference potential evaporation are based on ERA5. Spatial downscaling to model resolution took place with a nearest-neighbor approach for precipitation, and a lapse-rate based approach for temperature and pressure data. From this, the potential evaporation is estimated with the De Bruin method (De Bruin et al., 2016).

#### Soil

Soil parameters are based on SoilGrids250 (Hengl et al., 2017) and various (pedo) transfer functions, see Imhoff et al., 2020. Topography parameters are based on the Multi-Error-Removed Improved-Terrain Hydro digital elevation model (MERIT Hydro DEM) (Yamazaki et al., 2019) and the Iterative Hydrography Upscaling (IHU) method by Eilander et al. (2021) to derive flow direction and representative river length, slope and width parameters.

#### Landcover

Land cover-based parameters are based on VITO v2.0.2 (Buchhorn et al., 2019) and Corine Land Cover 2018 (European Environment Agency, 2018).

#### Glaciers

Initial fraction per grid cell covered by a glacier and the initial storage in these glaciers (in mm) are estimated using global RGI (RGI Consortium, 2017), GLIMS (Raup et al., 2007), and Swiss GLAMOS (Fischer et al., 2014) databases, together with glacier volume estimations from Grinsted (2013).

#### Calibration

Only the model parameter fKh0 (a multiplicative factor on the saturated vertical conductivity to obtain the saturated horizontal conductivity) is tuned. All other parameters are based on Imhoff et al. (2020) and Eilander et al. (2021), and can be directly derived with the HydroMT package (Eilander et al., 2023).

### Output variables

Discharge, actual evaporation, soil moisture (rootzone)

Total water storage will follow, see github issue: https://github.com/Deltares/Wflow.jl/issues/281

## wflow\_sbm v0.7.1 Po at 30 arc-seconds with ERA5

### Simulation options

* Period: 1990 – 2022
* Region: Po River
* Settings: default HydroMT derivation (Eilander et al., 2023), 1D floodplain schematization with kinematic wave land and local-inertial river routing, glaciers, reservoirs and lakes.
* Spin up: 2 years with same dataset from 1988 up to 1990.

### Resolution

* Spatial resolution: 30 arc-seconds
* Temporal resolution: daily

### Input datasets

#### Meteorology (and pre-processing)

Daily precipitation, temperature and reference potential evaporation are based on ERA5. Spatial downscaling to model resolution took place with a nearest-neighbor approach for precipitation, and a lapse-rate based approach for temperature and pressure data. From this, the potential evaporation is estimated with the De Bruin method (De Bruin et al., 2016).

#### Soil

Soil parameters are based on SoilGrids250 (Hengl et al., 2017) and various (pedo) transfer functions, see Imhoff et al., 2020. Topography parameters are based on the Multi-Error-Removed Improved-Terrain Hydro digital elevation model (MERIT Hydro DEM) (Yamazaki et al., 2019) and the Iterative Hydrography Upscaling (IHU) method by Eilander et al. (2021) to derive flow direction and representative river length, slope and width parameters.

#### Landcover

Land cover-based parameters are based on VITO v2.0.2 (Buchhorn et al., 2019) and Corine Land Cover 2018 (European Environment Agency, 2018).

#### Glaciers

Initial fraction per grid cell covered by a glacier and the initial storage in these glaciers (in mm) are estimated using global RGI (RGI Consortium, 2017), GLIMS (Raup et al., 2007), and Swiss GLAMOS (Fischer et al., 2014) databases, together with glacier volume estimations from Grinsted (2013).

#### Calibration

All parameters are based on Imhoff et al. (2020) and Eilander et al. (2021), and can be directly derived with the HydroMT package (Eilander et al., 2023).

### Output variables

Discharge, actual evaporation, soil moisture (root zone)

Total water storage will follow, see github issue: https://github.com/Deltares/Wflow.jl/issues/281

## Wflow\_sbm v0.7.1 Europe at 30 arc-seconds with ERA5

### Simulation options

* Period: 1990 – 2022
* Region: Europe
* Settings: default HydroMT derivation (Eilander et al., 2023), kinematic wave land and kinematic wave routing, glaciers, reservoirs and lakes.
* Spin up: 2 years with same dataset from 1988 up to 1990.

### Resolution

* Spatial resolution: 30 arc-seconds
* Temporal resolution: daily

### Input datasets

#### Meteorology (and pre-processing)

Daily precipitation, temperature and reference potential evaporation are based on ERA5. Spatial downscaling to model resolution took place with a nearest-neighbor approach for precipitation, and a lapse-rate based approach for temperature and pressure data. From this, the potential evaporation is estimated with the De Bruin method (De Bruin et al., 2016).

#### Soil

Soil parameters are based on SoilGrids250 (Hengl et al., 2017) and various (pedo) transfer functions, see Imhoff et al., 2020. Topography parameters are based on the Multi-Error-Removed Improved-Terrain Hydro digital elevation model (MERIT Hydro DEM) (Yamazaki et al., 2019) and the Iterative Hydrography Upscaling (IHU) method by Eilander et al. (2021) to derive flow direction and representative river length, slope and width parameters.

#### Landcover

Land cover-based parameters are based on VITO v2.0.2 (Buchhorn et al., 2019).

#### Glaciers

Initial fraction per grid cell covered by a glacier and the initial storage in these glaciers (in mm) are estimated using global RGI (RGI Consortium, 2017), GLIMS (Raup et al., 2007), and Swiss GLAMOS (Fischer et al., 2014) databases, together with glacier volume estimations from Grinsted (2013).

#### Calibration

All parameters are based on Imhoff et al. (2020) and Eilander et al. (2021), and can be directly derived with the HydroMT package (Eilander et al., 2023).

### Output variables

Discharge

## Wflow\_sbm v0.7.1 Tugela at 30 arc-seconds with CHIRPS

### Simulation options

* Period: 1990 – 2021
* Region: Tugale River
* Settings: default HydroMT derivation (Eilander et al., 2023), kinematic-wave land and kinematic-wave river routing scheme, glaciers, reservoirs and lakes.
* Spin up: 2 years with same dataset from 1988 up to 1990.

### Resolution

* Spatial resolution: 30 arc-seconds
* Temporal resolution: daily

### Input datasets

#### Meteorology (and pre-processing)

Daily precipitation is based on CHIRPS global, temperature and reference potential evaporation are based on ERA5. Spatial downscaling to model resolution took place with a nearest-neighbor approach for precipitation, and a lapse-rate based approach for temperature and pressure data. From this, the potential evaporation is estimated with the De Bruin method (De Bruin et al., 2016).

#### Soil

Soil parameters are based on SoilGrids250 (Hengl et al., 2017) and various (pedo) transfer functions, see Imhoff et al., 2020. Topography parameters are based on the Multi-Error-Removed Improved-Terrain Hydro digital elevation model (MERIT Hydro DEM) (Yamazaki et al., 2019) and the Iterative Hydrography Upscaling (IHU) method by Eilander et al. (2021) to derive flow direction and representative river length, slope and width parameters.

#### Landcover

Land cover-based parameters are based on VITO v2.0.2 (Buchhorn et al., 2019).

#### Glaciers

Initial fraction per grid cell covered by a glacier and the initial storage in these glaciers (in mm) are estimated using global RGI (RGI Consortium, 2017), GLIMS (Raup et al., 2007), and Swiss GLAMOS (Fischer et al., 2014) databases, together with glacier volume estimations from Grinsted (2013).

#### Calibration

All parameters are based on Imhoff et al. (2020) and Eilander et al. (2021), and can be directly derived with the HydroMT package (Eilander et al., 2023).

### Output variables

Discharge, actual evaporation, soil moisture (root zone)

Total water storage will follow, see github issue: https://github.com/Deltares/Wflow.jl/issues/281

# GEOframe

### Simulation options

* Period: 1990-01-01 – 2020-12-31 (calibration has been done during 2015-10-01-2018-09-30)
* Region: Po River basin

### Resolution

* Spatial resolution: The delineated subbasins area (polygons) is around 25 km2. However, the output files have been prepared with 30 arc-seconds spatial resolution.
* Temporal resolution: daily

### Input datasets

#### Meteorology (and pre-processing)

Daily precipitation and temperature time series measured at gauges.

#### Calibration

The 19 parameters of the model have been calibrated during 2015-2018.

### Output variables

ET: evapotranspiration (Total evapotranspiration flux, mm), has been converted to kg m-2 s-1.

SM: soil moisture (Volumetric soil moisture content, mm).

Q: discharge (Discharge flux, m3/s).

TWS: total water storage (Total water storage content, kg m-2).

Water Budget closure (via Jupyter notebooks)

### Noteworthy

Codes, simulations setup,data and outputs can be packaged and distributed for replication and peruse.

## mHM (0.015625deg and 0.125deg) forced with ERA5, EMO-1 and E-OBS

### Simulation options

* Period: 1990 - 2022
* Region: global/European setup
* Settings: default (see included modules above)
* Spin up: based on a 30 years simulation with 1950-1989 climatology for ERA5, while 10 years simulation with 1990-2000 climatology for EMO-1 and 40 years for E-OBS

### Resolution

* Spatial resolution: 0.015625degree; 0.125degree
* Temporal resolution: hourly (meteo inputs daily, internal weights are used to disaggregate to hourly)

### Input datasets\*

\* See Rakovec et al, (2022) and Boeing et al. (2022) for more information

#### Meteorology (and pre-processing)

Precipitation, temperature and reference potential evapotranspiration are based on three datasets: EMO-1 (Thieming et al, 2022 in it’s updated ~1km resolution, see for more details: https://jeodpp.jrc.ec.europa.eu/ftp/jrc-opendata/CEMS-EFAS/meteorological\_forcings/README-EMO-1arcmin.txt ) and ERA5 (Hersbach et al. 2020), the later was remapped on the 0.125deg grid using the nearest neighbor approach), and E-OBS (Cornes et al, 2018). Reference potential evapotranspiration was determined using the Hargreaves-Samani equation (Hargreaves and Samani, 1985). The internal model time step of mHM is an hourly one, and the temporal disaggregation (day to hour) is based on the weights derived from the native hourly ERA5 dataset.

#### Soil and topography

Soil parameters are based on the SoilGrids (Hengl et al., 2014). Topography parameters are based on GMTED2010 (https://www.usgs.gov/coastal-changes-and-impacts/gmted2010) is used to derive information about the slope, aspect. It was further conditioned on the HydroSHEDS (Lehner et al., 2008) river network (https://www.hydrosheds.org/downloads) to derive flow direction and flow accumulation.

#### Landcover and vegetation

mHM uses three dominant land cover classes (forest, permeable, and impervious) that were retrieved by a GLOBCOVER database ESA (2009). Additionally, vegetation characteristics for interception processes are based Leaf Area Index (LAI) from the GIMMS MODIS. from the global land cover facility (GLCF), available at http://iridl.ldeo.columbia.edu/SOURCES/.UMD/.GLCF/.GIMMS/.NDVIg/.global/index.html.

#### Groundwater processes

The baseflow recession constants are based on categorical classes derived from the GLIM databased from the Universität Hamburg (https://doi.org/10.1594/PANGAEA.788537); see Hartman and Moosdorf (2012) for more details.

### Output variables

Discharge, actual evapotranspiration, soil moisture, total water

## ParflowCLM – water resources over central Europe

### Simulation options

* Period: from 2007-01-01 to now + daily 10-day forecasts (deterministic + 50-member ensemble) + 7-months seasonal forecasts every 4 months (50-member ensemble)
* Region: Germany and neighboring regions
* Settings: 3D grid 2000 (X) x 2000 (Y) x 15 (Z) ; depth layers with increasing thickness from surface to 60m depth
* Spin up: first homogeneous/idealized spin-up with constant precipitation and without CLM, then repeating 3 times the period from 2007-01-01 to 2020-12-31 (1st) resp. 2021-12-31 (2nd, 3rd) with the fully heterogeneous model setup

### Resolution

* Spatial resolution: 0.611 km x 0.611 km
* Temporal resolution: hourly

### Input datasets

#### Meteorology (and pre-processing)

ECMWF forecasts from HRES (10-day deterministic forecast), ENS (10-day 50-member ensemble forecast), SEAS (7-months 50-member ensemble forecast), 8 (near-) surface variables preprocessed with CDO

#### Soil

Above depth to bedrock: SoilGrids250m reclassified to 12 USDA texture types, below depth to bedrock: 6 IHME (international Hydrogeological Map of Europe) aquifer types

#### Vegetation

CORINE Land Cover CLC2018 reclassified to 18 IGBP types

#### Calibration

No calibration needed

#### Others

Soil hydraulic properties from ROSETTA

### Output variables

ParFlow: pressure head

CLM: different evaporation terms, ET, latent and sensible heat, infiltration, surface temperature, soil temperature, snow cover (water equivalent)

All variables describing the surface and subsurface water budget (e.g., volumetric soil moisture, 3D subsurface water flux, surface and subsurface water storage, runoff) are calculated afterwards (postprocessing) on the basis of the pressure head and the soil hydraulic properties

## TETIS-mHM era5 Po 0p0625deg daily

### Simulation options

* Period: 1990 to 2020
* Region: Po River
* Settings: default.
* Spin up: Calibration of 9 corrector factors of the TETIS model and geology units for the mHM model was realized from 1980 to 1989.

### Resolution

* Spatial resolution: 0.0625 degrees
* Temporal resolution: Daily

### Input datasets

#### Meteorology

Precipitation, temperature and reference potential evapotranspiration are based on ERA5, the later was remapped on the 0.125deg grid using the nearest neighbor approach. Reference potential evapotranspiration was determined using the Hargreaves-Samani equation.

#### Soil

Soil parameters are based on the SoilGrids. Topography parameters are based on GMTED2010 is used to derive information about the slope, and aspect. It was further conditioned on the HydroSHEDS river network to derive flow direction and flow accumulation.

#### Land cover

Three dominant land cover classes (forest, permeable, and impervious) retrieved from the ESA GLOBCOVER database (2009) were used. Additionally, vegetation characteristics for interception processes are based Leaf Area Index (LAI) from the GIMMS MODIS from the global land cover facility (GLCF).

#### Groundwater

The baseflow recession constants are based on categorical classes derived from the GLIM databased from the Universität Hamburg.

#### Calibration

Calibration of 9 corrector factors of the TETIS model was realized from 1970 to 1990.

### Output variables

ET: evapotranspiration (Total evapotranspiration flux, kg m-2 s-1)

SM: soil moisture (Volumetric soil moisture content, %)

Q: discharge (Discharge flux, m-3 s-1)

TWS: total water storage (Total water storage content, kg m-2)

## Tetis era5 Tugela 0p0625deg daily

### Simulation options

* Period: 1990 to 2020
* Region: Tugela River
* Settings: default, including reservoirs upstream.
* Spin up: Warmup period 1960 to 1970. Calibration of 9 corrector factors of the TETIS model was realized from 1970 to 1990.

### Resolution

* Spatial resolution: 0.0625 degrees
* Temporal resolution: Daily

### Input datasets

#### Meteorology

Precipitation, temperature and reference potential evapotranspiration are based on ERA5, the later was remapped on the 0.125deg grid using the nearest neighbor approach. Reference potential evapotranspiration was determined using the Hargreaves-Samani equation.

#### Soil

Soil parameters are based on the SoilGrids. Topography parameters are based on GMTED2010 is used to derive information about the slope, and aspect. It was further conditioned on the HydroSHEDS river network to derive flow direction and flow accumulation.

#### Land cover

Three dominant land cover classes (forest, permeable, and impervious) retrieved from the ESA GLOBCOVER database (2009) were used. Additionally, vegetation characteristics for interception processes are based Leaf Area Index (LAI) from the GIMMS MODIS from the global land cover facility (GLCF).

#### Groundwater

The baseflow recession constants are based on categorical classes derived from the GLIM databased from the Universität Hamburg.

### Output variables

ET: evapotranspiration (Total evapotranspiration flux, kg m-2 s-1)

SM: soil moisture (Volumetric soil moisture content, %)

Q: discharge (Discharge flux, m-3 s-1)

TWS: total water storage (Total water storage content, kg m-2)

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# Storage protocol

All model outputs need to be converted to NetCDF and have been made publicly available and accessible by all participants.

## Variable list

|  |  |  |  |
| --- | --- | --- | --- |
| Name   | Standard name   | Long name   | Units   |
| et   | evapotranspiration   | Total evapotranspiration flux   | kg m-2 s-1   |
| sm   | soil moisture   | Volumetric soil moisture content   | %   |
| q   | discharge   | Discharge flux   | m-3 s-1   |
| tws   | total water storage   | Total water storage content   | kg m-2   |
| uparea   | upstream area   | Upstream catchment area   | m2   |
| mask   | mask   | Catchment mask   | -   |

## Region extents

Outputs for a different regions should match the minimum and maximum bounds. Note that the minimum and maximum cell coordinates should add (for the minimum) and subtract (for the maximum) half of the resolution in order to get the cell center.

Please make sure that any cells not within the region watershed (i.e. within the region extent but not within the watershed(s) that is contained within the region) should contain missing values.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Name   | Minimum bound   |   | Maximum bound   |   |
|    | **Longitude** **(degrees east)**  | **Latitude** **(degrees north)**  | **Longitude** **(degrees east)**  | **Latitude** **(degrees north)**  |
| Europe   | -11   | 33   | 42   | 73   |
| Rhine   | 3   | 46   | 13   | 53   |
| Po   | 6   | 43    | 13   | 47   |
| Tugela   | 28   | -30   | 32   | -27   |

## Name formatting

Outputs should be named all lower case in the following format:

[model]\_[meteo]\_[variable]\_[region]\_[spatial-resolution]\_[temporal-resolution]\_[start-date]\_[end-date].nc

Note that the upstream area and mask variables do not require the temporal-resolution, start-date and end-date parts.

**[model]**

|  |  |
| --- | --- |
| name   | Description |
| pcrglobwb   | PCR-GLOBWB   |
| mhm   | mHM   |
| jules   | JULES   |
| tetis   | TETIS   |
| wflowsbm   | wflow\_sbm   |
| parflowclm   | Parflow-CLM   |
| geoframe   | GEOframe   |

**[meteo]**

|  |  |
| --- | --- |
| name   | Description |
| era5   | ERA5   |
| eobs   | E-OBS   |
| chirps   | CHIRPS   |
| era5land   | ERA5-Land   |
| w5e5   | W5E5   |
| erai   | ERA-Interim   |
| hres   | HRES   |

**[variable]**

|  |  |
| --- | --- |
| name   | Description |
| et   | Evapotranspiration   |
| sm   | Soil moisture   |
| q   | Discharge   |
| tws   | Total water storage   |
| uparea   | Upstream catchment area   |
| mask   | Catchment mask   |

**[region]**

|  |  |
| --- | --- |
| name   | Description |
| europe   | Europe   |
| rhine   | Rhine   |
| po   | Po   |
| tugela   | Tugale   |

**[spatial-resolution]**

Resolutions should be given in either seconds, minutes or degrees. Examples are given below

|  |  |
| --- | --- |
| name   | Description |
| 30sec   | 30 arc-seconds   |
| 90sec   | 90 arc-seconds   |
| 05min   | 5 arc-minutes   |
| 10min   | 10 arc-minutes   |
| 0p125deg   | 0.125 degrees   |
| 0p0625deg   | 0.0625 degrees   |

**[temporal-resolution]**

Monthly timesteps should be reported as the first of the month

|  |  |
| --- | --- |
| name   | Description |
| daily   | Daily   |
| monthly   | Monthly   |

**[start-date] and [end-date]**

Dates should be given as digits (4 digit year, 2 digit month and 2 digit day) without dashes or slashes. For example January 2nd 1996 is: 19960102.

For all resolutions smaller than 60 arc-seconds (1 arc-minute) outputs should be split into monthly files, while for any larger resolutions outputs should be split into yearly files.

## NetCDF formatting

Please provide NetCDF files that follow the header shown here (check with ncdump -h FILE). Note that values between < and > should be filled in. Variable details are described in the table above.

Please report data row-wise, meaning dimensions start at positive latitude and negative longitude. (Note latitudes and longitudes can easily be inverted with cdo -s invertlat <infile> <outfile>). All latitudes and longitudes are reported using the World Geodetic System 84 (WGS 84).

The depth dimension is only used for the soil moisture files. Depth represents the depth of each soil layer from the top to bottom. Note that depths are NOT cumulative.

NetCDF compression is highly encouraged, but is decided upon by each participant individually.

*dimensions:*

*lon = <nlons> ;*

*lat = <nlats> ;*

*depth = <nlayers> ;*

*time = UNLIMITED ;*

*variables:*

*double lon(lon) ;*

*lon:standard\_name = "longitude" ;*

*lon:long\_name = "Longitude" ;*

*lon:units = "degrees\_east" ;*

*lon:axis = "X" ;*

*double lat(lat) ;*

*lat:standard\_name = "latitude" ;*

*lat:long\_name = "Latitude" ;*

*lat:units = "degrees\_north" ;*

*lat:axis = "Y" ;*

*double time(time) ;*

*time:standard\_name = "time" ;*

*lat:long\_name = "Time" ;*

*time:units = "days since 1970-01-01 00:00:00" ;*

*time:calendar = "proleptic\_gregorian" ;*

*time:axis = "T" ;*

*float <variable\_name>(time, lat, lon) ;*

*tas:\_FillValue = 1.e+20f ;*

*tas:missing\_value = 1.e+20f ;*

*tas:units = “<variable\_units>" ;*

*tas:standard\_name = "<variable\_standard\_name>" ;*

*tas:long\_name = “<variable\_long\_name>" ;*

*--ONLY FOR SOIL MOISTURE--*

*double depth(depth) ;*

*lat:standard\_name = "depth" ;*

*lat:long\_name = "Depth of each soil layer" ;*

*lat:units = "m" ;*

*lat:axis = "Z" ;*

*float sm(time, depth, lat, lon) ;*

*tas:\_FillValue = 1.e+20f ;*

*tas:missing\_value = 1.e+20f ;*

*tas:units = “<variable\_units>" ;*

*tas:standard\_name = "<variable\_standard\_name>" ;*

*tas:long\_name = “<variable\_long\_name>" ;*

*--ONLY FOR MASK--*

*short mask(lat, lon) ;*

*tas:\_FillValue = -1 ;*

*tas:missing\_value = -1;*

*tas:units = “<variable\_units>" ;*

*tas:standard\_name = "<variable\_standard\_name>" ;*

*tas:long\_name = “<variable\_long\_name>" ;*

*--ONLY FOR UPSTREAM AREA --*

*float uparea(lat, lon) ;*

*tas:\_FillValue = 1.e+20f ;*

*tas:missing\_value = 1.e+20f ;*

*tas:units = “<variable\_units>" ;*

*tas:standard\_name = "<variable\_standard\_name>" ;*

*tas:long\_name = “<variable\_long\_name>" ;*

*// global attributes:*

*:contact = "<contact name> (<contact email>)";*

*:institution = "<institution>";*

*:comment = "Data prepared for 4dHydro" ;*