Supplementary material

1 Description of input data

1.1 Mask map

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CWATM can run globally at 0.5° (30' or ≈ 50 km by 50 km at the equator) or 5' (≈ 10 km x10 km) or a set of coordinates or a mask map can be defined to use the global dataset but running CWATM locally. Figure S1 gives an example of a mask map for the Rhine basin. Each red grid cell (here: 5') is considered for calculation. Every other grid cell is not used.



Figure S1: Mask map for the Rhine basin at 5'

10 **1.2 Digital elevation model and river channel network**

The model uses a digital elevation model and it's derivate (e.g. standards deviation, slope) as variables for the snow processes and for the routing of surface runoff. The Shuttle Radar Topography Mission - SRTM (Jarvis et al. (2008)) is used for latitudes $\leq 60^{\circ}$ N and DEM Hydro1k (USGS, 2002) is used for latitudes > 60° N.

CWATM uses a local drainage direction map which defines the dominant flow direction in one of the eight neighboring grid

- 15 cells (D8 flow model). This forms a river network from the springs to the mouth of a basin. To be compliant with the ISIMIP framework (https://www.isimip.org), the 0.5° drainage direction map (DDM30) of Döll and Lehner (2002) is used. For higher resolution e.g. 5' different sources of river network maps are available e.g. HydroSheds (Lehner et al., 2008) DRT (Wu et al., 2011) and CaMa-Flood (Yamazaki et al., 2009). These approaches uses the same hydrological sound digital elevation model but differ in the upscaling methods. Zhao et al. (2017) show the importance of routing schemes and river networks in
- 20 peak discharge simulation. In CWATM the DDM30 is used for 0.5° and DRT is used for 5'. To calculate the kinematic wave in CWATM static maps of channel width, channel bankful depth, channel gradient, manning's coefficient and channel length are needed which are calculated using the river network, the flow accumulation, elevation data and average river discharge data. Figure S2 illustrated the channel gradient at 5' for two different regions.



Figure S2: Channel gradient at 5' in percentage

1.3 Lakes and reservoirs

5 The HydroLakes database (Messager et al., 2016;Lehner et al., 2011) provides 1.4 million global lakes and reservoirs with a surface area of at least 10ha. CWATM differentiate between big 'global' lakes and reservoirs which are connected to the river network and smaller 'local' lakes and reservoirs which are part of a single grid cell and part of the runoff concentration within a grid cell. Therefore the HydroLakes database is separated into "big" lakes and reservoirs with an area ≥ 100 km² for 0.5° (5 km² for 5') or upstream area ≥ 5000 km² 0.5° (200 km² for 5') and into "small" lakes which represents the non-big lakes. All lakes and reservoirs are set up grid cell level but big lakes can have the expansion of several grid cells.

1.4 Soil data

Soil data comes from the Harmonized World Soil Database 1.2 (HWSD) (FAO et al., 2012)- Version 1.2 7 March, 2012 which was developed by the Land Use Change and Agriculture Program of IIASA (LUC) and the Food and Agriculture Organization

- 15 of the United Nations (FAO). The HWSD is a 30 arc-second raster database with over 16000 different soil mapping units that combines existing regional and national updates of soil information worldwide the European Soil Database (ESDB), the 1:1 million soil map of China, various regional SOTER databases (SOTWIS Database), and the Soil Map of the World with the information contained within the 1:5000000 scale FAO-UNESCO Soil Map of the World. The resulting raster database is linked to harmonized soil property data. From the HWSD the standard soil properties like texture, porosity, soil minerals (%
- 20 of sand, clay), organic matter and bulk density are used.

A pedotransfer function from Zhang and Schaap (2017) is used to transfer the standard soil properties (soil texture, porosity, organic matter and bulk density) to the van Genuchten model parameters: maximal amount of moisture, residual amount of moisture, pore-size index, saturated conductivity of the soil (see Figure S3), inverse of air entry suction.



5 Figure S3: Saturated hydraulic conductivity (Ks) [cm/day] second soil layer 5-30 cm at 5'

1.5 Groundwater

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For groundwater modeling maps of the recession constant of the hydraulic conductivity and the storage coefficient are needed. Gleeson et al. (2011) and the database of GLHYMPS—Global Hydrogeology Maps of permeability and porosity (Gleeson et al., 2014) are providing the necessary data. Figure S4 shows the global recession constant.



Figure S4: Recession constant GLIM: [1/day] at 5'

1.6 Land cover

Land cover is used to calculate fraction of water, forest, irrigated area, rice irrigated area, sealed (impermeable area) and the remaining fraction for each cell. For each fraction the soil module runs separately. The total runoff of each cell is calculated by weighting the cell according to the different fractions. Data on urban area or imperious area is based on the 1 km version

5 of Elvidge et al. (2007), Forest land cover data are provided in high resolution by Hansen et al. (2013). Global maps of irrigated areas are used from Döll and Siebert (2002) and Siebert et al. (2005) with global data on crop coefficient based on MIRCA2000, Global data set of monthly irrigated and rainfed crop areas around the year 2000 (Portmann et al., 2010). A historical, gridded land use data set with 5' data on 15 different crop groups is used from the Hyde 3.2 database (Klein Goldewijk et al., 2017).

1.7 Global Albedo

10 A global dataset to calculate potential evaporation using albedo is provided by Muller et al. (2012).

1.8 Data sets of meteorological forcing

For calculating potential evaporation with Penman-Monteith some meteorological forcing data are needed:

- max, min, average temperature [K]
- humidity (relative[%] or specific[%])
- surface pressure [Pa]

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- radiation (short wave and long wave downwards) [W m-2]
- wind speed [m/s]

If potential evaporation is already calculated in a previous run or from external source:

- Precipitation [Kg m-2 s-1] or [m] or [mm] (can be adjusted by a conversion factor in the settings file)
 - Temperature (average) [K]
- Potential evaporation [Kg m-2 s-1] or [m] or [mm] (can be adjusted by a conversion factor in the settings file)

From observation: (ISI-MIP 2a):

- WFDEI.GPCC (Weedon et al., 2014)
 - WFD—Watch forcing data set: 0.5 3/6 hourly meteorological forcing from ECMRWF reanalysis (ERA40) bias-corrected and extrapolated by CRU TS and GPCP (rainfall) and corrections for under catch
 - PGMFD v.2 Princeton (Sheffield et al., 2006)
 - GSWP3 (Kim et al., 2012)
- 30 MSWEP (Beck et al., 2017)

From GCM (ISIMIP 2b):

- HadGem2-ES (Met Office Hadley Centre, UK)
- IPSL-CM5A-LR (Institut Pierre-Simon Laplace, France)
- 35 GFDL-ESM2M (NOAA, USA)
 - MIROC-ESM-CHEM (JAMSTEC, AORI, University of Tokyo, NIES, Japan)

For downscaling of 0.5° meteorological data to 5' or even to 30'' the dataset of WorldClim version2 (Fick and Hijmans, 2017) is used. They provide average monthly dataset for different meteorological variables for 1970-2000 for different spatial resolutions from 30'' to 10'. The dataset is used to estimate the spatial heterogeneity inside a 0.5° or 5' grid cell.

5 **1.9 Datasets for model calibration and validation**

Observed historical daily river discharge data and lake water levels were available originating from several sources. Data made available through the GRDC (Global Runoff Data Centre, 2007) were used. Several discharge station data were obtained through bilateral exchanges between IIASA and national hydrological services. As much as possible, these historical discharge data have been used for model calibration and verification.

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1.10 Socio economic datasets

Data on population and gross domestic product (GDP) are based on the SSP Database of IIASA (Riahi et al., 2017). Methods and data for spatial disaggregation of country based data to gridded 5' data are taken from Jones and O'Neill (2016); Gao (2017); Kummu et al. (2018) and Gidden et al. (2018).

- 15 The gridded livestock densities of cattle, buffalo, sheep, goats, pigs and poultry in the year 2000 and their drinking water requirements are obtained from FAO (2007) and Steinfeld et al. (2006). The number of each livestock type per country from 1979-2010 are provided by FAO (2012) and is downscaled to 5' or 30' using the distribution of livestock density in 2000. Gridded industrial water data for 2000 is using the data from Shiklomanov (1997). The approach of Shen et al. (2008) and Wada et al. (2011) is including GDP, electricity production, energy consumption and household consumption. Domestic water
- 20 demand needs population data and the rate of domestic water withdrawal per capita from FAO (2007) and Gleick et al. (2009).

Calibration results for Rhin basin 0.5° resolution

Calibration: 1995-2010



River: Rhine Station: Lobith

Validation: 1980-1994

River: Rhine Station: Lobith



- a) Observed (blue) and simulated (red) daily or monthly streamflow time series during variable calibration periods (depending on the availability of observed data)
- (b) Scatter plot showing the relationship between observed and simulated streamflow.
- (c) Monthly climatology of observed (blue) and simulated (red) streamflow for the water year (from October to September) during the calibration period. Shaded area shows the standard deviation for each month for observed and simulated streamflow
- 10 The Kling-Gupta Efficiency (KGE) is used as the objective function. Other model performance metrics are summarized in the table, including NS (Nash-Sutcliffe coefficient of efficiency) and its log form (NSlog), R² (coefficient of determination), Bias, RMSE (root mean squared error), and MAE (mean absolute error). Observed and simulated streamflow statistics are shown, including mean, minimum, maximum, and different quantiles (5%, 50%, 95%, 99%).

Some basins do not show a validation period. Here we used all available observation data for calibration.

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Calibration: 1995-2010

River: Danube Station: Kienstock, AT



Calibration: 1995-2010

River: Danube Station: Zimnicea, RO



Validation: 1980-1994

River: Danube Station: Kienstock, AT



Validation: 1980-1994

River: Danube Station: Zimnicea, RO



Figure S6: Calibration result Danube

Calibration: Calibration:2001-2013

River: Yukon station: Pilot station

Validation: 1985-1997

River: Yukon station: Pilot_station



Calibration results for Amazon basin, Brazil Calibration: 1985-1997

River: Amazonas: Obidos

Validation: 1970-1984





Figure S7: Calibration result Yukon and Amazon

Calibration results for Murray River, Australia

Calibration: 2000-2010

River: Murray River station: Wakool Junction

Validation: 1990-1999

River: Murray River station: Wakool Junction



Figure S8: Calibration result Murray River

Calibration results for White Nile basin / Uganda

Calibration: 1996-2005

River: Nile Station: Jinja, Uganda



Calibration: 1996-2005

River: Nile Station: Laropi



Figure S9: Calibration result White Nile

Calibration results for Zambezi basin

Calibration: 1979-1990

Station: Lukulu / Zambezi



Station: Matundo-Cais / Zambezi



Figure S10: Calibration result Zambezi

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