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Global catchment modelling using World-Wide HYPE (WWH), open data and stepwise parameter estimation

Berit Arheimer[1*], Rafael Pimentel[1,2], Kristina Isberg[1], Louise Crochemore[1], Jafet C.M. Andersson[1], Abdulghani Hasan[1,3], and Luis Pineda[1,4]

[1] *Swedish Meteorological and Hydrological Institute (SMHI), Folkborgsvägen 17, 60176 Norrköping, Sweden.*

[2] *University of Cordoba, Edf. Leonardo Da Vinci, Campus de Rabanales, 14071, Córdoba, Spain.*

[3] *Lund University Box 117, SE-221 00, Lund, Sweden.*

[4] *Proyecto Yachay, Hacienda San José, Urcuquí, Ecuador.*

[*]Corresponding author: Berit Arheimer (berit.arheimer@smhi.se)

Abstract

Recent advancements in catchment hydrology (such as understanding hydrological processes, accessing new data sources, and refining methods for parameter constraints) make it possible to apply catchment models for ungauged basins over large domains. Here we present a cutting-edge case study applying catchment-modelling techniques at the global scale for the first time. The modelling procedure was challenging but doable and even the first model version show better performance than traditional gridded global models of river flow. We used the open-source code of the HYPE model and applied it for >130 000 catchments (with an average resolution of 1000 km^2), delineated to cover the Earths landmass (except Antarctica). The catchments were characterized using 20 open databases on physiographical variables, to account for spatial and temporal variability of the global freshwater resources, based on exchange with the atmosphere (e.g. precipitation and evapotranspiration) and related budgets in all compartments of the land (e.g. soil, rivers, lakes, glaciers, and floodplains), including water stocks, residence times, interfacial fluxes, and the pathways between various compartments. Global parameter values were estimated using a step-wise approach for groups of parameters regulating specific processes and catchment characteristics in representative gauged catchments. Daily time-series (> 10 years) from 5338 gauges of river flow across the globe were used for model evaluation (half for calibration and half for independent validation), resulting in a median monthly KGE of 0.4. However, the world-wide HYPE (WWH) model shows large variation in model performance, both between geographical domains and between various flow signatures. The model performs best in Eastern USA, Europe, South-East Asia, and Japan, as well as in parts of Russia, Canada, and South America. The model shows overall good potential to capture flow signatures of monthly high flows, spatial variability of high flows, duration of low flows and constancy of daily flow. Nevertheless, there remains large potential for model improvements and we suggest both redoing the calibration and reconsidering parts of the model structure for the next WWH version. The calibration cycle should be repeated a couple of times to find robust values under new fixed parameter conditions. For the next iteration, special focus will be given to precipitation, evapotranspiration, soil storage, and dynamics from hydrological features, such as lakes, reservoirs, glaciers, and floodplains. This first model version clearly indicates challenges in large scale modelling, usefulness of open data and current gaps in processes understanding. Parts

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of the WWH can be shared with other modellers working at the regional scale to appreciate local knowledge, establish a critical mass of experts and improve the model in a collaborative manner. Setting up a global catchment model has to be a long-term commitment of continuous model refinements to achieve successful and truly useful results.

1. Introduction

Hydrological models are useful tools to better understand processes behind observation, to reconstruct past events and to predict future events, as well as to explore the impact of various scenarios of change in flow controlling factors, such as climate or human activities. Catchment models were traditionally often applied in small well-monitored rivers under pristine conditions, to understand mechanisms in flow generation (e.g. Bergström and Forsman, 1973; Beven and Kirby, 1979; Lindström et al., 1997) or to support flow forecasts at warning services (e.g. Arheimer et al., 2011). However, a combination of societal requests and scientific initiatives has changed this context for catchment modelling recently. As catchment models are mimicking observation through calibration procedures, they have high credibility among practitioners and water managers. Hence, they are used operationally in many societal sectors, to provide for instance design values for infrastructure, water allocation schemes, navigation routes, flood warnings, environmental-status indices or optimal industrial-water use. Currently, all these users of catchment model outputs also face climate change and seek data and information to best implement climate adaptation for their specific business. Hence, catchment models are also used to estimate climate change impact.

The catchment research community has embraced this applied focus and, at the same time, expanded the geographical domain to multi-catchments. The applied focus is illustrated by the new decade of the International Association of Hydrological Sciences (IAHS) called "Panta Rhei", which addresses change in hydrology and society (Montanari et al., 2013) and focuses on the human impact on the water cycle instead of traditional pristine conditions. The spatial expansion, on the other hand, is driven by accelerating advances in hydrological research as described by Archfield et al. (2015). For instance, comparative hydrology (Falkenmark and Chapman, 1989) or large sample hydrology (Gupta et al., 2014) show the potential to advance science by addressing a larger domain with multiple catchments than just exploring one single catchment at a time. Similarly, the previous scientific decade of IAHS "Predictions in Un-gauged Basins", PUB (Hrachowitz et al., 2013; Bloeschl et al., 2013), resulted in methods to maintain the procedures typical for catchment modelling when parameters are transferred to areas without observed time-series of river flow, such as regionalization, parameter constraints, and Monte Carlo approaches for empirical quality control, to ensure that the process description is realistic and account for uncertainties. This opened up for catchment models to be tested and applied also at the continental scale (e.g. Pechlivanidis and Arheimer, 2015; Abbaspour et al., 2015; Donnelly et al., 2016), where normally other types of hydrological models were applied, using other modelling procedures and showing other advantages than the methods used by the catchment modelling community (see e.g. Archfield et al., 2015). Such large-scale models are for instance water allocation models (e.g. Arnell, 1999; Vörösmarty et al., 2000; Döll et al., 2003) or meteorological land-surface models (e.g. Liang et al., 1994; Woods et al.,

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1998; Pitman, 2003; Lawrence et al., 2011) sometimes with more advanced routing schemes (e.g. Alferi et al., 2013). These more traditional global and continental modelling approaches can now be compared to hydrological catchment models in large-scale applications (Fig. 1).

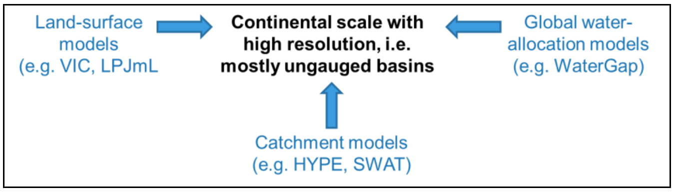

Figure 1. Different modelling communities who can now start comparing their methods.

Other important factors, which nowadays allow catchment modelling at the global scale, are computational capacity and open global data sources. The methods for applying and evaluating catchment models are computationally heavy. The advances in application routines and evaluation frameworks, such as GLUE (Beven and Binley, 1992), DREAM (Laloy and Vrugt, 2012), or methods in the SAFE toolbox (Pianosi et al., 2015) have become possible due to the fact that the catchment models themselves are normally quick to run even on a personal computer. With increasing computational capacity, these methods are now possible to apply also in a multi-catchment approach for a large domain. Most important for catchment modelling, however, is the recent explosion of open and readily available data sources globally, which makes it possible to delineate the catchment borders, find input data at relevant scale to set up the catchment models, and to assign time-series of observed flow at some catchment outlets. This enables the use of recognised methods in catchment modelling for parameter estimation and model evaluation.

In the early 1970's, model parameters were calibrated using a rather simple curve fitting towards observed time-series of river flow in a specific catchment outlet (e.g. Bergström and Forsman, 1973). Since then the methods for parameter estimation have become more sophisticated, especially when the objective is regionalisation across many catchments at large scale (e.g. Beck et al., 2016). Some common approaches use: (i) the same parameters based on geographic proximity (e.g. Merz and Blöschl, 2004; Oudin et al., 2008); (ii) regression models between parameter values and catchment characteristics (Hundecha and Bárdossy, 2004; Samaniego et al., 2010; Hundecha et al., 2016); (iii) simultaneous calibration in multiple representative catchments with similar climatic and/or physiographic characteristics (e.g. Arheimer and Brandt, 1998; Fernandez et al., 2000; Parajka et al., 2007). In this study, we apply a variety of the latter, using a stepwise approach (e.g. Strömqvist et al., 2012; Pechlivanidis and Arheimer, 2015; Donnelly et al, 2016; Andersson et al., 2017) trying to isolate hydrological processes and calibrate them separately against observed river flow in selected representative basins across the entire globe, although, some hydrological features as large lakes and floodplains were calibrated individually.

The hypothesis tested in the present study states that, it is now possible and timely to apply catchment modelling techniques at the global scale. We address this hypothesis by applying a catchment model world-wide and then evaluating the results using statistical metrics for time-series and flow signatures. To our knowledge, this is the first time a catchment model was applied world-

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wide covering the entire globe with relatively high resolution, providing an average subbasin size of ~1000 km^2 (WWH version 1.3). Our specific objective is to provide a harmonized way to predict hydrological variables (especially river flow and the water balance) globally, which can also be shared for further refinement to assist in regional and local water management wherever hydrological models are currently lacking. To address this objective, we (i) compile open global data from >30 sources, including for instance topography and river routing, meteorological forcing, physiographic land characteristics and in total some 20 000 time-series of river flow world-wide, (ii) apply the open-source code of the Hydrological Predictions for the Environment, HYPE model (Lindström et al., 2010), (iii) estimate model parameter values using a new stepwise calibration technique addressing the major hydrological processes and features world-wide, and (iv) compute metrics and flow signatures, and compare model performance with physiographic variables to judge model usefulness. We then pose the scientific question: How far can we reach in predicting river flow globally, using integrated catchment modelling, open global data and readily available time-series for calibration?

2. Data

2.1 Physiographic data

For catchment delineation and routing, topographical data is needed, but none of the hydrologically refined databases cover the entire land surface of Earth and therefore we had to merge several sources of information (Table 1). Most of the globe is covered by GWD-LR (Global Width Database of Large Rivers) 3 arc sec (Yamazaki et al. 2014), apart from the very northern part close to the Arctic Sea, for which HYDRO1K 30 arc sec (USGS) is available. For Greenland, we used GIMP-DEM (Greenland Ice Mapping Project) 3 arc sec (Howat et al. 2014) and for Iceland the National data from the meteorological office. For the latter we merged the catchments to better fit the overall resolution, going from 27 000 catchments to 253.

Additional data was gathered to help with defining catchments as the delineation of catchments can be difficult in some environments. In flat areas we consulted previous mapping and hydrographical information of floodplains, prairies and deserts (Table 1). Karstic areas are unpredictable due to lack of subsurface information of underground channels crossing surface topography and thus needed to be defined and evaluated separately. Finally, flood risk areas were recognized as potentially important, enabling the use of model results in combination with hydraulic models, and thus also had to be identified so that model results can be extracted for such applications.

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Table 1. Databases used for catchment delineation, routing and elevation in WWH version 1.3.

Type	Dataset/Link	Provider/Reference
Topography (Flow accumulation, flow direction, digital elevation, river width)	GWD-LR (3 arcsec) http://hydro.iis.u-tokyo.ac.jp/~yamadai/GWD-LR/ GIMP-DEM (3 arcsec) https://bpcrc.osu.edu/gdg/data/gimpdem HYDRO1K (30 arcsec) https://lta.cr.usgs.gov/HYDRO1K SRTM (3 arcsec) https://lta.cr.usgs.gov/SRTM	Yamazaki et al., 2014 Howat et al., 2015 United State Geological Survey – (USGS) USGS
Non-contributing areas in Canada	Areas of Non-Contributing Drainage (AAFC Watersheds Project – 2013) https://open.canada.ca/data/dataset/67c8352d-d362-43dc-9255-21e2b0cf466c	Government Canada
Watershed delineation (Iceland)	IMO subbasins and main river basins http://en.vedur.is/hydrology/	Icelandic Met Office (IMO)
Karst	World Map of Carbonate Rock Outcrops v3.0 http://digital.lib.usf.edu/SFS0055342/00001	Ford (2006)
Global Flood Risk	Global estimated risk index for flood hazard http://ihp-wins.unesco.org/layers/geonode:fl1010irmt	UNEP/GRID-Europe
Floodplains	Global Lake and Wetland Database (GLWD) https://www.worldwildlife.org/publications/global-lakes-and-wetlands-database-lakes-and-wetlands-grid-level-3	Lehner and Döll, 2004
Desert areas	World Land-Based Polygon Features https://geo.nyu.edu/catalog/stanford-bh326sc0899	University of New York

For catchment characteristics governing the hydrological processes in HYPE, the ESA CCI Landcover version 1.6.1 epoch 2010 (300 m) was the baseline, but several other data sources were used to adjust and add information to some hydrologically important features, such as glaciers, lakes, reservoirs, irrigated crops, and climate zone (Table 2).

Table 2. Databases used to assign land cover, waterbodies and climate to catchments in WWH version 1.3.

Type	Dataset/Link	Provider/References
Land cover characteristics	ESA CCI Landcover v 1.6.1 epoch 2010 (300 m) https://www.esa-landcover-cci.org/?q=node/169	ESA Climate Change Initiative - Land Cover project
Glaciers	Randolph Glacier Inventory (RGI) v 5.0 https://www.glims.org/RGI/randolph50.html	RGI Consortium
Greenland icesheet	Greenland Glacier Inventory	Rastner et al, 2012
Lakes	ESA CCI-LC Waterbodies 150 m 2000 v 4.0 https://www.esa-landcover-cci.org/?q=node/169	ESA Climate Change Initiative - Land Cover project
Lakes	Global Lake and Wetland Database 1.1 (GLWD) https://www.worldwildlife.org/publications/global-lakes-and-wetlands-database-large-lake-polygons-level-1	Lehner and Döll, 2004
Lake depths	Global Lake Database v2(GLDB) http://www.flake.igb-berlin.de/ep-data.shtml	Kourzeneva, 2010, Choulga, 2014

Reservoirs and dams	Global Reservoir and Dam database v 1.1 (GRanD) http://www.gwsp.org/products/grand-database.html	Lehner et al., 2011
Irrigation	GMIA v5.0 http://www.fao.org/nr/water/aquastat/irrigationmap/index10.stm MIRCA v1.1 http://www.uni-frankfurt.de/45218031/data_download	Siebert et al., 2013 Portmann et al., 2010
Climate classification	Köppen-Geiger Climate classification, 1976-2000, v June 2006 http://koeppen-geiger.vu-wien.ac.at/	Kottek et al., 2006

2.2 Forcing data

The WWH model uses time-series of daily precipitation and temperature to make calculations on a daily time-step. All catchment models require initializations of the current state of the snow, soil and lake (and sometimes river) storages. At the global scale, a seamless dataset for several decades is necessary for consistent model forcing, to also cover hydrological features with large storage volumes. For WWH version 1.3 precipitation and temperature were achieved from the Hydrological Global Forcing Data (HydroGFD; Berg et al., 2018), which is an in-house product of SMHI that combines different climatological data products across the globe. This global dataset spans a long climatological period up to near-real-time and forecasts (from 1961 to 6 months ahead). The period used in this study, is primarily based on the global (50 km grid) re-analysis product ERA-interim (Dee et al., 2011) from ECMWF, which is further bias adjusted versus other products using observations, e.g. versions of CRU (Harris and Jones, 2014) and GPCC (Schneider et al, 2014). The HydroGFD dataset is produced using a method for bias adjustment, which is similar to the method by Weedon et al. (2014) but additionally uses updated climatological observations, and, for the near-real-time, interim products that apply similar methods. This means that it can run operationally in near-real-time. The dataset is continuously upgraded and in the present study, we used the HydroGFD version 2.0.

2.3 Observed river flow

Catchment models need time-series of hydrological variables for parameter estimation and model evaluation. Metadata and time-series from gauging stations were collected from readily available open data sources globally (Table 3). In total, information from 21 704 gauging stations could be assigned to a catchment outlet. Of these, time-series could be downloaded for 11 369 while 10 336 could only assist with metadata, such as upstream area, river name, elevation or natural of regulated flow. The time-series were screened for missing values, inconsistency, skewness, trends, inhomogeneity, and outliers (Crochemore et al., manuscript). Only stations representing the resolution of the model (≥1000 km^2) and with records of at least 10 consecutive years between 1981 and 2012 were considered for model evaluation. With these criteria, 5338 time-series were finally used for evaluating model performance, of which 2863 represented completely independent model validation and 2475 were also involved when estimating some of the model parameters.

Table 3. Databases used for time-series of water discharge and location of gauging station when estimating parameters and evaluating the model performance of WWH version 1.3.

Data type	Short Name/Link	Coverage	Provider/References
Time-series + metadata	GRDC https://www.bafg.de/GRDC/EN/Home/homepage_node.html	Global	Global Runoff Data Center
“	EWA https://www.bafg.de/GRDC/EN/04_spcldtbss/42_EWA/ewa.html	Europe	GRDC – EURO-FRIEND-Water
“	Russian River data by Bodo, ds553.2 https://rda.ucar.edu/datasets/ds553.2/	Former Soviet Union	Bodo, 2000
“	R-ArcticNet v 4.0 http://www.r-arcticnet.sr.unh.edu/v4.0/index.html	Arctic region	Pan-Arctic Project Consortium
“	RIVDIS v 1.1 https://daac.ornl.gov/RIVDIS/guides/rivdis_guide.html	Global	Vörösmarty et al., 1998
“	USGS https://waterdata.usgs.gov/nwis/sw	USA	U.S. Geological Survey
“	HYDAT https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/monitoring/survey/data-products-services/national-archive-hydat.html	Canada	Water Survey of Canada (WSC)
“	Chinese Hydrology Data Project https://depts.washington.edu/shuiwen/index.html	China	Henck et al., 2011
“	Spanish Water Authorities https://www.mapama.gob.es/es/ministerio/funciones-estructura/organizacion-organismos/organismos-publicos/confederaciones-hidrograficas/default.aspx	Spain	Ecological Transition Ministry
“	WISKI https://vattenwebb.smhi.se/station/	Sweden	Swedish Meteorological and Hydrological Institute
Metadata	CLARIS-project http://www.claris-eu.org/	La Plata Basin	CLARIS LPB- project FP7 Grant agreement 212492
“	CWC handbook http://cwc.gov.in/main/webpages/publications.html	India	Central Water commission (CWC)
“	SIEREM http://www.hydrosciences.fr/sierem/	Africa	Boyer et al., 2006
“	Regional data https://uia.org/s/or/en/1100058436	Congo Basin	International Commission for Congo-Ubangui-Sangha Basin (CICOS)
“	National data http://www.bom.gov.au/water/hrs/	Australia	BOM (Bureau of Meteorology)
“	Red Hidrometrica SNHN 2013 http://geo.gob.bo/geonetwork/srv/dut/catalog.search#/metadata/ff98cf17-f9a8-4a8d-b96c-bf623dd6b13b	Bolivia	Servicio Nacional de Hidrografía Naval
“	Estacoes Fluviometrica http://www.snirh.gov.br/hidroweb/	Brazil	ANA (Agencia Nacional de Aguas)
“	Red Hidrometrica http://www.dga.cl/Paginas/default.aspx	Chile	DGA (Direccion General de Aguas)
“	Catalogo Nacional de Estaciones de Monitoreo Ambiental http://www.ideam.gov.co/geoportal	Colombia	IDEAM (Instituto de Hidrologia, Meteorologia y Estudios Ambientales)

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"	Estaciones_Hidrologicas http://www.serviciometeorologico.gob.ec/geoinformacion-hidrometeorologica/	Ecuador	INAMHI (Instituto Nacional de Meteorología e Hidrología)
"	National data http://www.senamhi.gob.pe/?p=0300	Peru	SENAMHI (Servicio Nacional de Meteorologia e Hidologia del Peru)
"	National data http://www.inameh.gob.ve/web/	Venezuela	IGVSB (Instituto Geográfico de Venezuela Simon Bolivar)
"	Conabio 2008 http://www.conabio.gob.mx/informacion/metadata/gis/esthidgw.xml?_httpcache=yes&_xsl=/db/metadata/xsl/fgdc_html.xsl&_indent=no	Mexico	Instituto Mexicano de Tecnología del Agua/CONABIO
"	Niger HYCOS http://nigerhycos.abn.ne/user-anon/htm/	Niger river	World Hydrological Service System (WHYCOS)
"	National data https://www.dwa.gov.za/Hydrology/	South Africa	Department Water & Sanitation, Republic of South Africa
"	National data http://publicutilities.govmu.org/English/Pages/Hydrology-Data-Book-2006---2010.aspx	Mauritius	Mauritius Ministry of Energy and Public Utilities

3. Methods

The WWH is developed incrementally, and the current version 1.3 was based on previous versions, where version 1.0 only included the most basic functions to run a HYPE model and was forced by MSWEP (Beck et al., 2017) and CRU (Harris and Jones, 2014). Version 1.2 included distributed geophysical and hydrographical features, and finally, version 1.3 (described below) included estimated parameter values and was forced by the meteorological dataset Hydro-GFD, which also provides operational forecasts at a 50 km grid (Berg et al., 2017). Dynamic catchment models need to be initialised to account for adequate storage volumes, which may, for instance, dampen or supply the river flow based on catchment memory (e.g. Iliopoulou et al., 2019). The WWH was initialized by running for a 15-year warm-up period 1965-1980, which was judged to be enough for more than 90% of the catchments. However, a longer initialization period is needed for large lakes with small catchments, large glaciers, and sinks or rarely-contributing areas.

The current model runs at a Linux cluster (using nodes of 8 processors and 16 threads) with calculations in approximately 1 800 000 hydrological response units (HRUs) and 130 000 catchments covering the worlds land surface, except for Antarctica. The model runs in parallel in 32 hydrologically-independent geographical domains with a run time of about 3 hours for 30-year daily simulations. The methods applied for modelling and evaluation mostly follow common procedures used by the catchment modelling community, as described below.

3.1 Catchment delineation and characteristics

Catchment borders were delineated using the World Hydrological Input Set-up Tool (WHIST), software developed at SMHI that is linked to the Geographic Information System (GIS) Arc-GIS from ESRI. By defining force-points for catchment outlets in the resulting topographic database (c.f. Table 1) and criteria for minimum and maximum ranges in catchment size, the tool delineates catchments and the link (routing) between them. By adding information from other types of databases, WHIST also aggregates data or uses the nearest grid for assigning characteristics to each catchment. WHIST handles both gridded data and polygons, and was used to link all data described in Section 2, such as land-cover, river width, precipitation, temperature, and elevation, to each delineated catchment. WHIST then compiles the input data files to a format that can be read by the HYPE source code. The software runs automatically, but also has a visual interface for manual corrections and adjustments. It may also adjust the position of the gauging stations to match the river network of a specific topographic database.

When setting up WWH, force-points for catchment delineation were defined according to:

- *Locations of gauging stations in the river network*: in total, catchments were defined for all 21 704 gauging stations which had an upstream area greater than 1000 km^2 (except for data sparse regions (500 – 1000 km^2). Their coordinates were corrected to fit with the river network of the topographic data, using WHIST and manually. Quality checks of catchment delineation were done towards station metadata and 88% of the estimated catchment areas were within +/-10% discrepancy towards metadata. These catchments were used in further analysis for parameter estimation or model evaluation; however, not all of these sites provided open access to time-series (see Section 2.3).

- *Outlets of large lakes/reservoirs*: New lake delineation was done to solve the spatial mismatch between data of the water bodies from various sources (c.f. Table 2). The centroid of the lakes included in GLWD and GRanD was used as initialization points for a Flood Fill algorithm, applied over the ESA CCI Water Bodies, followed by manual quality checks. The outlet location was defined using the maximum upstream area for each lake. In total, around 13 000 lakes and 2500 reservoirs > 10 km^2 were identified globally. The new dataset was tested against detailed lake information for Sweden, which represents one of the most lake-dense regions globally. Merging data from the two databases and adjusting to the topographic data used was judged more realistic for the global hydrological modelling than only using one dataset.

- *Large cities and cities with high flood risk*: The UNEP/GRID-Europe database (Table 1) was used to define flood-prone areas for which the model may be useful in the future. The criteria for assigning a force point was city areas of > 100 km^2 (regardless of the risks on the UNEP scale) or city areas of 10-100 km^2 with risk 3-5 and an upstream area > 1000 km^2. This was only considered if there was no gauging station within 10 km from the city. This gave another 2 439 forcing points to the global model.

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- *Catchment size*: the goal was to reach an average size of some 1000 km^2, for practical (computational) and scientific reasons, reflecting uncertainty in input data. Criteria in WHIST were set to reach maximum catchment size of 3000 km^2 in general and 500 km^2 in coastal areas with < 1000 m elevation (to avoid crossing from one side to another of a narrow and high island or peninsula). Post-processing was then done for the largest lakes, deserts, and floodplains, following specific information on their character (see data sources in Table 2).

Using this approach, the land surface of the Earth (i.e. 135 million km^2 when excluding Antarctica) was divided into 131 296 catchments with an average size of 1020 km^2. Flat land areas of deserts and floodplains ended up with somewhat larger catchments, about 4500 km^2 and 3500 km^2, respectively. Around 23.8% of the land surface did not drain to the sea but to sinks (Fig. 2), the largest single one being the Caspian Sea. This water was evaporated from water surfaces but also percolating to groundwater reservoirs. Moreover, several areas across the globe are of Karstic geology with wide underground channels, which does not follow the land-surface topography. Sinks within Karst areas according to the World Map of Carbonate Rock outcrops (Table 1) were linked to "best neighbour" and inserted to the river network. The Canadian prairie also encompasses a lot of sinks due to climate and topography, but here we could apply a national dataset from Canada with well-defined noncontributing areas to adjust the routing in this area.

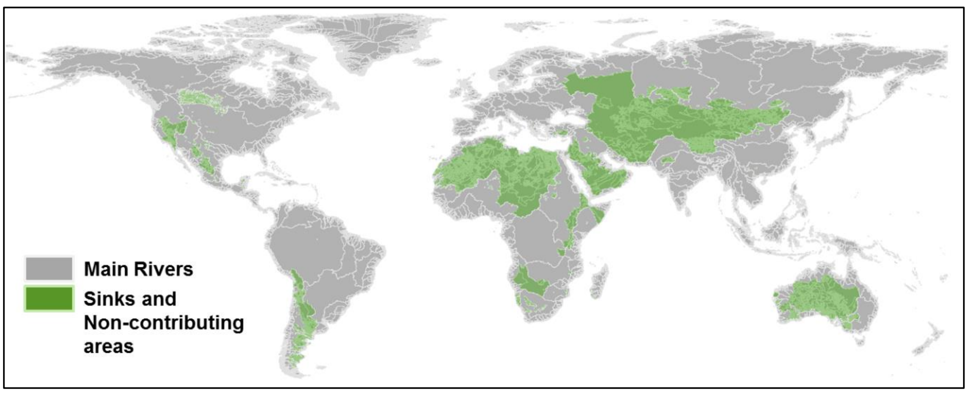

Figure 2. Major river basins and areas not contributing to river flow from land to the sea.

The land-cover data from ESA CCI LC v1.6 (Table 2) was used as the base-line for HRUs. It has 36 classes and subclasses and three of these were adjusted using additional data to improve the quality; (1) by using glacier outlines from RGI v5 we avoided overestimation of the glacier area; (2) by using GMIA and MIRCA we added irrigation where this information where missing and underestimated; (3) by combining several sources and spatial analyses we differentiated one general class of waterbodies into four: large lakes, small lakes, rivers, and coastal sea, which makes more sense in catchment modelling. Five elevation zones were derived to differentiate land-cover classes with altitude (0-500 m, 500-1000 m, 1000-2000 m, 2000-4000 m and 4000–8900 m) as the hydrological response may be very different at different altitude due to vegetation growth and soil properties. The land-cover at these elevations was thus treated as a specific HRU globally. In total, this resulted in 169 HRUs.

All catchments were characterized according to Köppen-Geiger (Table 2) to assign a PET algorithm (see section 3.2) but the characteristics did not include soil properties, which is common in catchment hydrology. The approach when setting up HYPE was to use the possibility to assign hydrologically active soil depth for the HRUs instead, based on the variability in vegetation, climate and elevation they represent. However, a few distinct soil properties were unavoidable beside the general soil to describe the hydrological processes; these were impermeable conditions of urban and rock environments, and infiltration under water and rice fields.

3.2 The HYPE model

The HYPE model development was initiated in 2002, primary to support the implementation of the EU Water Framework Directive in Sweden (Arheimer and Lindström, 2013). It was originally designed to estimate water quality status, but is now also used operationally at the Swedish hydrological warning service at SMHI for flood and drought forecasting (e.g. Pechlivanidis et al., 2014). The water and nutrient model is applied nationally for Sweden (Strömqvist et al., 2012), the Baltic Sea basin (Arheimer et al., 2012) and Europe (Donnelly et al., 2013). It also provides operational hydrological forecasts for Europe at short-term and seasonal scale and it has been subjected to several large scale applications across the world, e.g. the Indian subcontinent (Pechlivanidis and Arheimer, 2015) and the Niger River (Andersson et al., 2017). One of the main drivers for HYPE applications has been climate-change impact assessments, for which its results have been compared to other models in selected catchments across the globe (Geflan et al., 2017; Gosling et al., 2017; Donnelly et al., 2017).

The HYPE model code (Lindström et al., 2010) represents a rather traditional integrated catchment model, describing major water pathways and fluxes in a catchment. It is forced by precipitation and temperature at daily or hourly time-step, and start by calculating the water balance of Hydrological Response Units, which is the finest calculation unit in each catchment. In the WWH set-up, the HRUs were defined by land-cover, elevation and climate, without specific consideration to further definition of soil properties. This was guided by recent studies indicating that soil water storage and fluxes rather relate to vegetation type and climate conditions than soil properties (e.g. Troch et al., 2009; Gao et al., 2014). HYPE has maximum three layers of soil and these were all applied in the WWH, with a different hydrological response from each one for each HRU. The first layer corresponds to some 25 cm, the second to some 1-2 meters and the third can be deep also accounting for ground water. A specific routine can account for deep aquifers, but this was not applied in the WWH due to lack of local or regional information of aquifer behavior. HYPE has a snow routine to account for snow storage and melt, while a glacier routine account for ice storage and melt. Mass balances of glaciers were based on the observations provided in the Randolph Glacier Inventory (Arendt et al., 2015) and fixed separately in the model set-up. There are a number of algorithms available to calculate potential evapotranspiration (PET) in HYPE. For the WWH we used the algorithms that had been judged most appropriate in previous HYPE applications, giving Jensen-Haise (Jensen and Haise, 1963) in temperate areas, modified Hargreaves (Hargreaves and Samani, 1982) in arid and equatorial areas, and Priestly Taylor (Priestly and Taylor, 1972) in polar and snow /ice dominated areas. River flow is routed from upstream catchments to downstream along the river network, where lakes and reservoirs may dampen the flow according to a rating curve. A specific

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routine is used for floodplains to allow the formation of temporary lakes, which may be crucial especially in inland deltas (Andersson et al., 2017). Evaporation takes place from all water surfaces, including snow and canopy. The HYPE source code, documentation and user guidance are freely available at http://hypecode.smhi.se/.

3.3 Step-wise parameter estimation

The method to assign parameter values for the global model domain aimed at finding (i) robust values also valid for ungauged basins, as well as (ii) reliable process description of dominating flow generation processes and water storage along the flow paths. The first aim was addressed by simultaneous calibration in multiple representative catchments world-wide. Spatial heterogeneity was accounted for by separate calibration of catchments representing different climate, elevation, and land-cover globally. The second aim was addressed by applying a step-wise approach following the HYPE process description along the flow paths, only calibrating a few parameters governing a specific process at a time (Arheimer and Lindström, 2013). The estimated parameter values were then applied wherever relevant in the whole geographical domain, i.e. world-wide.

Different catchments were selected globally to best represent each process calibrated (Fig. 3). For HRUs, separate calibration was done for the snow-dominated areas (>10% of precipitation falling as snow), as the snow processes give such strong character to the runoff response and simultaneous calibration with catchments lacking snow may thus underestimate other flow-controlling processes. The HRUs based on the ESA CCI 1.6 data was aggregated from 36 classes into 10 (Table 4) for more efficient calibration and to ensure that some 50% of the gauged catchment selected was representing the appointed land-cover. Some local hydrological features such as large lakes and floodplains were calibrated individually. When evaluating the effect of this, we discovered some major bias for the Great Lakes in North America and Malawi and Victoria lakes in Africa. Finally, we introduced the 11th step to calibrate the evaporation of these separately (Fig 3).

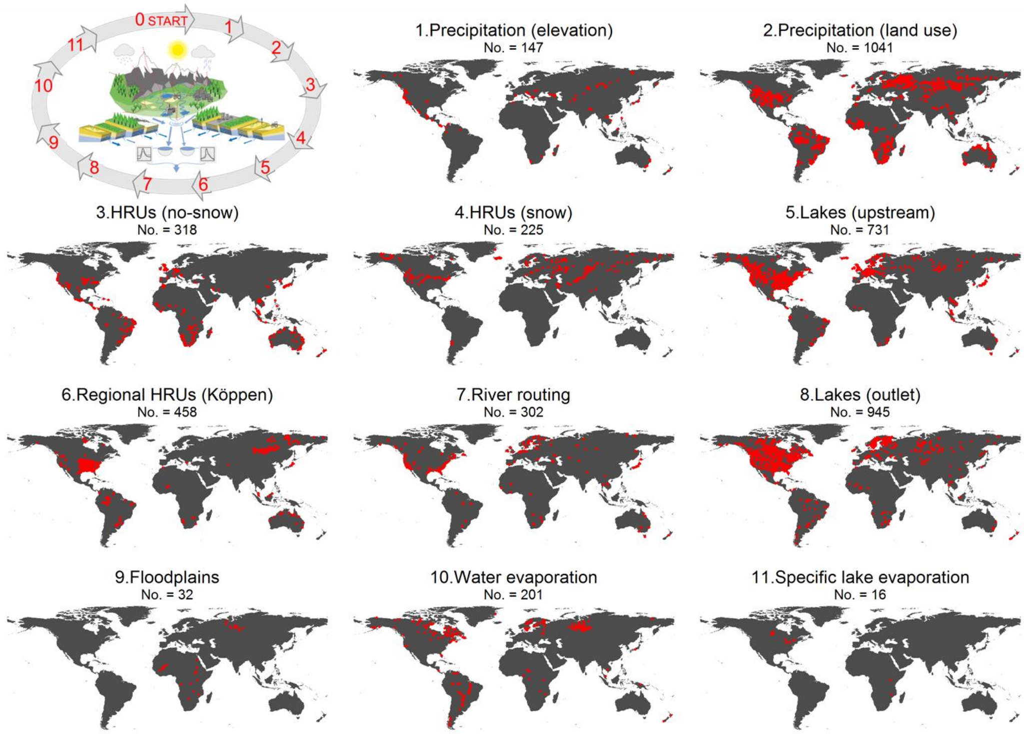

Figure 3. Number of gauging stations and their location that was used in each step of the stepwise parameter estimation procedure and evaluation against in-situ observations world-wide.

In total, 6519 river gauges were used in the calibration process, but normally only affecting few model parameters in the stepwise procedure. 1181 of these gauges did not meet the ambition to represent the average catchment resolution and 10 consecutive years between 1981 and 2012, but was still included in some step due to lack of data. Automatic calibration was applied for each subset of parameters and representative catchments in each step, using the Differential Evolution Markov Chain (DEMC) approach (Ter Braak, 2016) to obtain the optimum parameter value in each case. The DEMC requires several parameters to be fixed and the choice of these parameters was based on a compromise between convergence speed and the accuracy of the resulting parameter set. Global PET parameter values were fixed first, before starting the step-wise procedure, using the MODIS global evapotranspiration product (MOD16) by Mu et al., (2011) for parameter constraints. The parameter ranges were defined as the median and the 3rd quartile of the 10% best agreements between HYPE and MODIS in terms of RE. The first selection was done with 400 runs and then repeated for a second round. In addition, a priori parameters (Table 5) were set for glaciers and soils without calibration, taken from previous applications (e.g. Donnelly et al., 2016; MacDonald et al., 2018). The bare deserts soil was manually calibrated only using 4 stations in the Sahara desert. The area and volume of glaciers were evaluated in 296 glaciers and soil parameters in some 30 catchments. The root zone storage of soils was further calibrated in the parameter setting of each HRU (in step No 4 and 5).

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While the calibration period was 1981-2012, it was always preceded by 15 years of initialization. Different metrics were chosen as calibration criteria, depending on the character of the parameter and how it influences the model. For instance, Relative Error (RE) was used as a metric in the calibration of precipitation and PET parameters, since the aim was to correctly represent water volumes. On the contrary, Correlation Coefficient (CC) was used when the timing was the main goal (i.e. for river routing or dampening in lakes). If both water volume and timing were required, Kling-Gupta Efficiency (KGE; Gupta et al., 2009) was used (i.e. for soil discharge from HRUs).

Table 4. Aggregated land covers used for HRUs, their representation in the upstream catchment and the number of gauges available for each land cover when estimating parameter values of WWH v1.3.

HRU calibration	Aggregated Land cover from ESA CCI 1.6	Land cover	No. gauges (snow area)	No. gauges (no snow)
Bare	Bare areas Consolidated bare areas Unconsolidated bare areas	35%	7	32
Crop	Cropland, rain fed Herbaceous cover Tree or shrub cover Cropland, irrigated or post-flooding irrigated Rice	50%	52	30
Grass	Grass	50%	-	1
Mosaic	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%) Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%) Mosaic tree and shrub (>50%) / herbaceous cover (<50%) Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	50%	39	29
Shrub	Shrubland Shrubland evergreen Shrubland deciduous Shrub or herbaceous cover, flooded, fresh/saline/brackish water	50%	54	17
Sparse	Lichens and mosses Sparse vegetation (tree, shrub, herbaceous cover) (<15%) Sparse shrub (<15%) Sparse herbaceous cover (<15%)	35%	40	11
TreeBrDecMix	Tree cover, broadleaved, deciduous, closed to open (>15%) Tree cover, broadleaved, deciduous, closed (>40%) Tree cover, broadleaved, deciduous, open (15-40%) Tree cover, mixed leaf type (broadleaved and needleleaved)	50%	26	28
TreeBrEvFlood	Tree cover, broadleaved, evergreen, closed to open (>15%) Tree cover, flooded, fresh or brakish water Tree cover, flooded, saline water	50%	37	30
TreeNeDec	Tree cover, needleleaved, deciduous, closed to open (>15%) Tree cover, needleleaved, deciduous, closed (>40%) Tree cover, needleleaved, deciduous, open (15-40%)	50%	46	-

TreeNeEv	Tree cover, needleleaved, evergreen, closed to open (>15%) Tree cover, needleleaved, evergreen, closed (>40%) Tree cover, needleleaved, evergreen, open (15-40%)	50%	-	10
Urban	Urban	50%	21	30

3.4 Model evaluation

The model was evaluated against independent observed river flow, which was not used in the calibration procedure. The agreement between modelled and observed time-series was evaluated using the statistical metric KGE and its components r, β and α, which are directly linked with CC (Pearson Correlation Coefficient), RE (Relative Error) and RESD (Relative Error of Standard Deviation), respectively (Gupta et al., 2009). KGE is defined as:

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

where:

$$r = CC = \frac{cov(x_o, x_s)}{\sigma_s \sigma_o} \qquad \text{(Eq. 2)}$$

$$\beta = \frac{\mu_s}{\mu_o}\,; RE = (\beta - 1) \cdot 100 \qquad \text{(Eq. 3)}$$

$$\alpha = \frac{\sigma_s}{\sigma_o}\,; RESD = (\alpha - 1) \cdot 100 \qquad \text{(Eq. 4)}$$

x represents the discharge time series, μ the mean value of the discharge time series, and σ the standard deviation of the discharge time series. The sub-indexes *o* and *s* represent observed and simulated discharge time series, respectively.

In addition, a number of flow signatures (Table 5) was calculated to explore which part of the hydrograph is well captured by the model. Flow signatures are used by the catchment modelling community to condense the hydrological information from time-series (Sivapalan, 2005) and the choice of flow signatures was guided by previous studies by Olden and Poff (2003) and Kuentz et al. (2017). In this study, flow signatures were calculated at 5338 gauging stations globally, based on catchment size and at least 10 years of continuous time-series (see section 2.3).

The model capability in capturing observed flow signatures was then related to upstream physiographical and climatological factors, such as area, mean elevation, drainage density, land-cover, climatic region or aridity index. Catchment modellers tend to study differences and similarities in flow signatures as well as in catchment characteristics to improve understanding of hydrological processes (e.g. Sawicz et al., 2014; Berghuijs et al., 2014; Pechlivanidis and Arheimer, 2015; Rice et al., 2015). Linking catchment descriptors and model performance in hydrological response signatures help the modeler to examine whether the process description and model structure are valid across the landscape or if the regionalization of parameter values must be reconsidered for some parts of a large domain. In addition, this exercise will guide the users to judge under which conditions the model is reliable and thus of any use for decision making. In the present study, the physiographic characteristics of catchments were all extracted from the input data files of the WWH version 1.3.

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For each gauging station with calculated flow signatures, the catchment characteristics were accumulated for all upstream catchments to account for any potential physiographical influence on the flow signal at the observation site (Table 3). Gauging stations were grouped according to the distribution of each physiographic characteristic and model performances in flow signature representation were computed for each of these groups.

Table 5. Flow signatures (FS) from observed time-series and physiographic descriptors (T: topography; LC: Land cover; C: climate) from databases in Section 2.1.

Variable name	Description	Range
skew (FS)	Skewness = mean/median of daily flows	[0.63 - 70000]
MeanQ (FS)	Mean specific flow in mm	[0 - 1024.41]
CVQ (FS)	Coef. of variation = standard deviation/mean of daily flows	[0.01 - 46.4]
BFI (FS)	Base Flow Index: 7-day minimum flow divided by mean annual daily flow averaged across years	[0 - 0.84]
Q5 (FS)	5th percentile of daily specific flow in mm	[0 - 218.04]
HFD (FS)	High Flow Discharge: 10th percentile of daily flow divided by median daily flow	[0 - 1]
Q95 (FS)	95th percentile of daily specific flow in mm	[0 - 2654.81]
LowFr (FS)	Total number of low flow spells (threshold equal to 5 % of mean daily flow) divided by the record length	[0 - 1]
HighFrVar (FS)	Coef. of Variation in annual number of high flow occurrences (threshold 75th percentile)	[0 - 5.48]
LowDurVar (FS)	Coef. of Variation in the annual mean duration of low flows (threshold 25th percentile)	[0 - 3.78]
Mean30dMax (FS)	Mean annual 30-days maximum divided by median flow	[0 - 29.49]
Const (FS)	Constancy of daily flow (see Colwell, 1974)	[0.01 - 1]
RevVar (FS)	Coef. of variation in annual number of reversals (change in sign in the day-to-day change time series)	[0 - 5.48]
RBFlash (FS)	Richard-Baker flashiness: sum if absolute values of day-to-day changes in mean daily flow divided by the sum of all daily flows	[0 - 2]
RunoffCo (FS)	Runoff ratio: mean annual flow (in mm yr^{-1}) divided by mean annual precipitation	[0 - 1362.52]
ActET (FS)	Actual evapotranspiration: mean annual precipitation minus mean annual flow (in mm yr^{-1})	[-100 - 2660.03]
Area (T)	Total upstream area of catchment outlet in km^2	[13.5 - 4671536.7]
meanElev (T)	Mean elevation of the catchment in m	[3.63 - 5046.16]
stdElev (T)	Standard deviation of the elevation of the catchment in m	[1.66 - 1595.89]
Meanslope (T)	Mean slope of the catchment	[0 - 224.24]
Drainage density (T)	Total length of all streams in the catchment divided by the area of the catchment	[2.19 - 259798.14]
13 land cover variables (LC)	% of the catchment area covered by the following land cover types (see Table XX): Water, Urban, Snow & Ice, Bare, Crop, Mosaic, TreeBrEvFlood, TreeBrdecMix, TreeNeEv, TreeNeDec, Shurb, Grass and Sparse	[0 - 1]
Pmean (C)	Mean annual precipitation in mm yr^{-1}	[51.5 - 5894.86]
SI.Precip (C)	Seasonality index for precipitation: $SI = \frac{1}{\bar{R}} \cdot \sum_{n=1}^{12} \left\| \bar{x}_n - \frac{\bar{R}}{12} \right\|$ $\bar{x}_n$: mean rainfall of month n; $\bar{R}$: mean annual rainfall	[-16.93 - 31]
Tmean (C)	Mean annual temperature in degrees	[0.08 - 50.06]
AI (C)	Aridity Index: PET/P, where PET is the mean annual potential evapotranspiration and P the mean annual precipitation	[0.05 - 1.28]
5 Köppen regions (C)	% of the catchment area within the following Köppen regions: A (Tropical), B (Arid), C (Temperate), D (Cold-continental) and E (Polar)	[0 - 1]

4. Results

4.1 Global river flow and general model performance

WWH version 1.3 successfully describes major hydrological features globally and important spatial variability in factors controlling the runoff mechanisms, although there is still room for improvements over the coming decade(s). The catchment modelling approach with careful consideration to hydrography, resulted in a new database with delineated hydrographical features (e.g. Fig. 4) of major importance for hydrological modelling. The merging of several data sources resulted in consistency between available information on water bodies, topographic data and the river network (e.g. for glaciers, floodplains, lakes, and gauging stations) so that this information can be used in catchment modelling and provide results of river flow at a resolution of some 1000 km^2 globally.

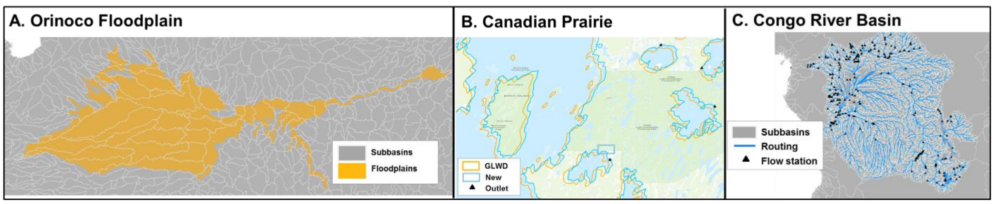

Figure 4. Some examples of WWH version 1.3 details in describing hydrography at local and regional scale from supporting GIS layers: A) subbasins of the Orinocco river defined as a connected floodplain; B) adjustment of lake areas (New) from merging several data sources (see Section 2.1 and 3.1) and the original GLWD in the Canadian Prairie; C) river routing and access to flow gauges in the Congo river basin.

The WWH version 1.3 resulted in a realistic spatial pattern of river flow world-wide, clearly identifying desert areas and the largest rivers (Fig. 5). Compared to other global estimates of average water flow in major rivers, HYPE gives results in the same order of magnitude, but of course, comparisons should be based on the same time period to account for natural variability due to climate oscillations. The Amazon, Congo and Orinocco rivers came out as the three largest ones, where the river flow of the Amazon river is almost 6 times larger than any other river. Compared to recent estimates by Milliman and Farnsworth (2011), HYPE estimated a higher annual average of river flow in Mississippi, St Lawrence, Amur, and Ob, but less in the rest of the top-ten largest rivers of the world, especially relatively lower values were noted for Ganges-Bahamaputra. For World-Wide HYPE, Yangtze river came out as No 11 and Mekong as No 12, and it should be noted that the river flow to Río de la Plata was separated into Paraná River and Uruguay river (the former ranked as No 13 of the largest rivers).

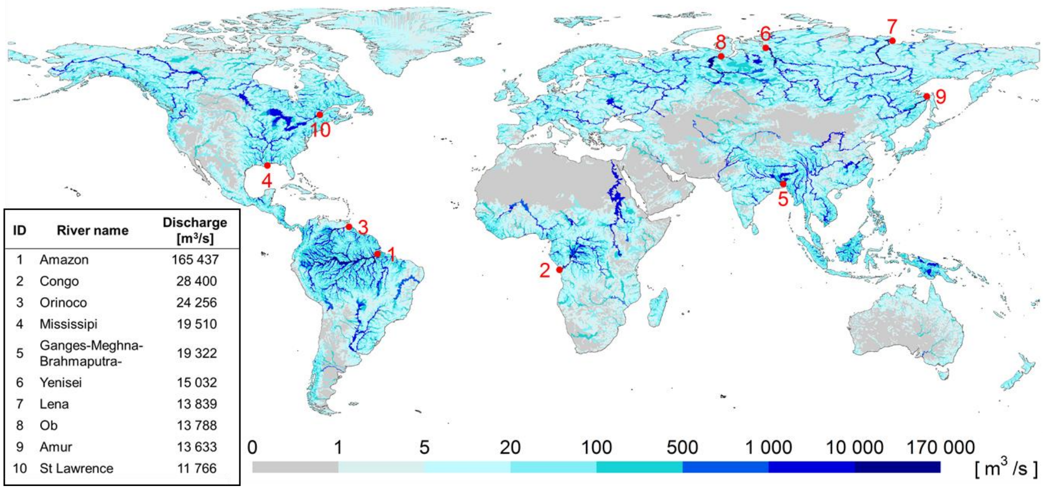

Figure 5. Annual mean of river discharge across the globe for the period 1981-2015 estimated with the catchment model WWH version 1.3 (on average 1020 km^2 resolution).

On average, for the whole globe and 5338 gauging stations with validated catchment areas and at least ten years of data, the model performance was estimated to a median monthly KGE of 0.40 (Fig. 6). Model performance was surprisingly similar for the gauges used in parameter estimation and independent ones, with median KGE of 0.41 (2475 stations) and 0.39 (2863 stations), respectively. This indicates that the model results are robust and the same model performance can be assumed also in ungauged basins. Given that global open input data was used for model setup and rough assumptions were made when generalizing hydrological processes across the globe, the overall model performance meets the expectations. Similar results were recently achieved when Beck et al. (2016) was testing a scheme for global parameter regionalization world-wide; in an ensemble of ten global water allocation or land surface models, the median performance of monthly KGE was found to be 0.22 using 1113 river gauges. The best median monthly KGE was then 0.32 for catchment scale calibration of regionalized parameters, using a gridded HBV model globally (Beck, 2016). Even though it is difficult to compare results when not using the same validation sites or time-period, the catchment modelling approach of the present study seems to have better performance than other gridded global modelling concepts of river flow.

The red spots in Figure 6 indicate where the HYPE model fails, such as in the US mid-west (Kansas to be precise), north-east of Brazil and parts of Africa, Australia and central Asia. When decomposing the KGE, it was found that the correlation was in general fine. However, the relative error in standard deviation was causing the main problems showing that the HYPE model does not capture the variations of the hydrograph, and instead, generates a too even flow. The relative error also seemed problematic, which indicates problems with the water balance. The model has severe problems with dry regions and areas with large impact from human alteration and water management, where the model underestimates the river flow. Such regions are known to be more difficult for hydrological modelling in general (Bloeschl et al., 2013), but in addition, precipitation data do not seem to fully capture the influence of topography and mountain ranges. The patterns in model performance were

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further investigated in the analysis of model performance versus flow signatures and physiographic factors (Section 4.3).

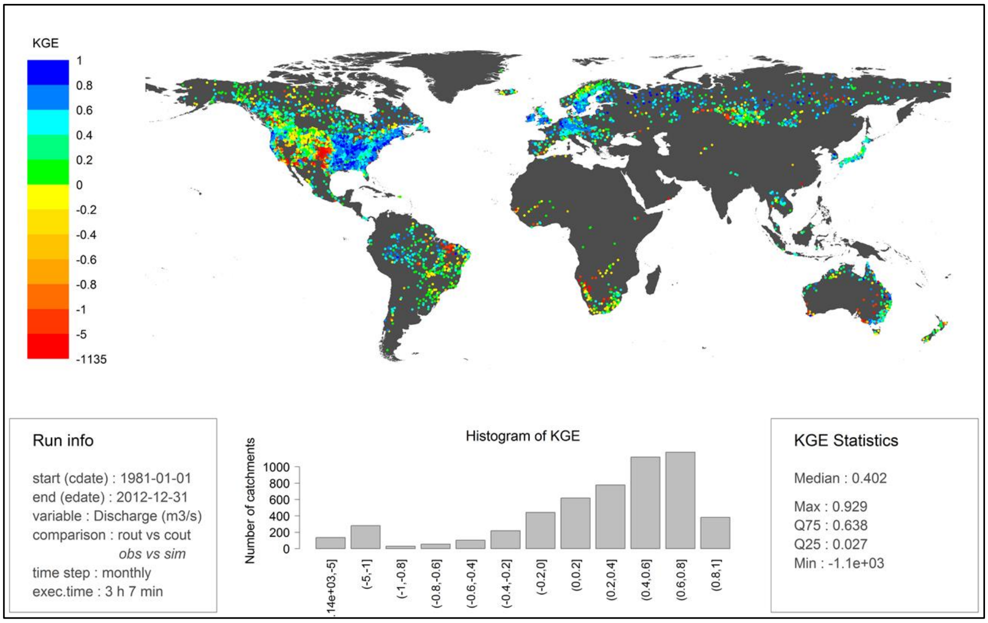

Figure 6. Model performance of WWH version 1.3 using the KGE metric of monthly values of ≥ 10 years in each of the 5338 gauging sites for the period 1981-2012. Blue and green indicates that the model provides more information than the long-term observed mean value.

4.2 Global parameter values from step-wise calibration

Both model performance in representative catchments and improvement achieved through calibration varied a lot for each hydrological process considered in the step-wise parameter estimation (Table 6). Although, a large number of river gauges was collected for parameter estimation, only a few could be considered as representative with enough quality assurance. More gauges in the calibration procedure would probably have given another result. Nevertheless, the results show promising potential in applying the process descriptions of catchment models also at the global scale.

In spite of the wide spread in geographical locations across the globe, a priori values were reasonable for hydrological processes describing glaciers and soils. As shown in Table 6, the water balance (RE) was improved considerably by first calibrating PET globally, and then precipitation vs altitude of catchment and land-cover type. Simultaneous calibration of soil storage and discharge in HRUs increased the KGE both in areas with and without snow by 0.1 on average. For calibration of river routing and rating curves of lake outflows, the correlation coefficient was used to avoid erroneous

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compensation of the water balance, as the parameters involved should only set the dynamics of flow and not volume. Especially lake processes benefited from calibration. Less convincing was the metrics from calibration of the floodplains, which were not always improved by the floodplain routine applied. Overall, the results indicate that global parameters are to some extent possible for describing hydrological processes world-wide, using a catchment model and globally available data of physiographic characteristics to describe spatial variability. Nevertheless, the WWH v.1.3 model has still considerable potential for improvements and to really make use of more advanced calibration techniques, the water balance needs to be improved first as too much volume error makes the tuning of dynamics difficult.

Table 6. Metrics of model performance before and after calibrating various hydrological processes simultaneously at a number of selected river gauges, using the stepwise parameter-estimation procedure globally. Parameter values and names in the HYPE model are given in Appendices.

Hydrological Process	**No. gauges**	**Median value of metric(s)**	
		Before	**After**
Potential Evapo-Transpiration (3 PET-algorithms: median of ranges constrained with MODIS)	0	RE: 11.5 %	RE: 0.5%
Glaciers (only evaluated vs mass balance data)	296	RE: 0.38% CC: 0.51	-
Soils (average, rock, urban, water, rice)	25	RE: -14.1% KGE: 0.2	
Bare soils in deserts (calibrated manually)	4	RE: 236.1%	RE: -18.9
1. Precipitation: catchment elevation	147	RE: -6.7%	RE: 4.4%
2. Precipitation: land-cover altitude	1041	RE: 24.3%	RE: 10.1%
3. HRUs in areas without snow	318	KGE: 0.16	KGE: 0.27
4. HRUs in areas with snow: ET, recession and active soil depth	225	KGE: 0.16	KGE: 0.24
5. Upstream lakes	731	CC: 0.71	CC: 0.72
6. Regionalised ET (in 12 Köppen climate regions)	458	KGE: 0.58	KGE: 0.62
7. River routing	302	CC: 0.70	CC: 0.71
8. Lake rating curve	945	CC: 0.50	CC: 0.59
9. Floodplains (partly calibrated manually)	32	KGE: -0.03	KGE: 0.03
10. Evaporation from water surface	201	RE: -20.7%	RE: -12.2%
11. Specific lake evaporation	16	RE: 24.8%	RE: 4.8%

4.3 Model evaluation against flow signatures

The WWH1.3 is more prone to success or failure in simulating specific flow signatures than to specific physiographic conditions, which is visualized by vertical rather than horizontal stripes in Figure 7. In general, the model shows reasonable KGE and CC for spatial variability of flow signatures across the globe (i.e. a lot of blue in the two panels to the left in Fig. 7). However, the RE and the standard deviation of the RE (RESD) are less convincing (i.e. the two panels to the right). This means that the model can capture the relative difference in flow signature and the spatial pattern globally, but not always the magnitudes, nor the spread between highest and lowest values. The relative errors are mostly due to underestimations, except for skewness, low flows and actual potential evapotranspiration; the two latter are always over-estimated when not within ±25% bias. Overall, the model shows good potential to capture spatial variability of high flows (Q95), duration of low flows (LowDurVar), monthly high flows (Mean30dMax) and constancy of daily flows (Const). These results were found robust and independent of metrics or physiography.

The model shows most difficulties in capturing skewness in observed time-series (skew), the number of high flow occurrences (HighFrVar), and base flow as average (BFI), or absolute low flows (Q5). Short-term fluctuations (RevVar and RBFlash) are also rather difficult for the model to capture. Some results are not consistent between metrics; for coefficient of variation (CVQ) the RE was good while the RESD was poor. This indicates that the model does not capture the amplitude in variation between sites even if the bias is small. The opposite was found for high flow discharge (HFD) and low-flow spells (LowFr), i.e. poor performance in volumes but RESD showing that the variability is captured.

For the remaining flow signatures studied, it was interesting to note that the model performance could be linked to physiographic characteristics, indicating that the model structure and global parameters are valid for some environments but not for others. For instance, the volume of mean specific flow (RE of MeanQ) is especially difficult to capture in regions with needle-leaved, deciduous trees (TreeNeDec) and for medium and large flows in the Köppen region B (Arid), large flows in D (Cold-continental) and small flows in E (Polar). Moreover, the analysis shows that the model tends to fail with the mean flow in catchments with high elevation, high slope, small fraction water and urban land-cover, and little or much of snow and ice. This shows where efforts need to be taken to improve the model in its next version. For other water-balance indices, it was interesting to note that the ratio between precipitation and river flow (RunoffCo) show good results (RE ± 25%) all over Köppen region C (Temperate) but otherwise is often underestimated for some parts of the quartile range of physiographic variables studied. On the contrary, precipitation minus flow (ActET) is over-estimated in parts of the quartile range, except for the good results in Köppen region C, needle-leaved, deciduous trees (TreeNeDec) and regions with snow and ice (i.e. where mean specific runoff failed). Figure 7 clearly shows the compensating errors between processes governing the runoff coefficient and actual evapotranspiration, with one being over-estimated when the other is underestimated for the same specific physiographic conditions. This indicates the need for recalibrating the HRUs of WWH in its next version, but also reconsidering the initial parameters for evapotranspiration and the quality of the precipitation grid and its linkage with the catchments.

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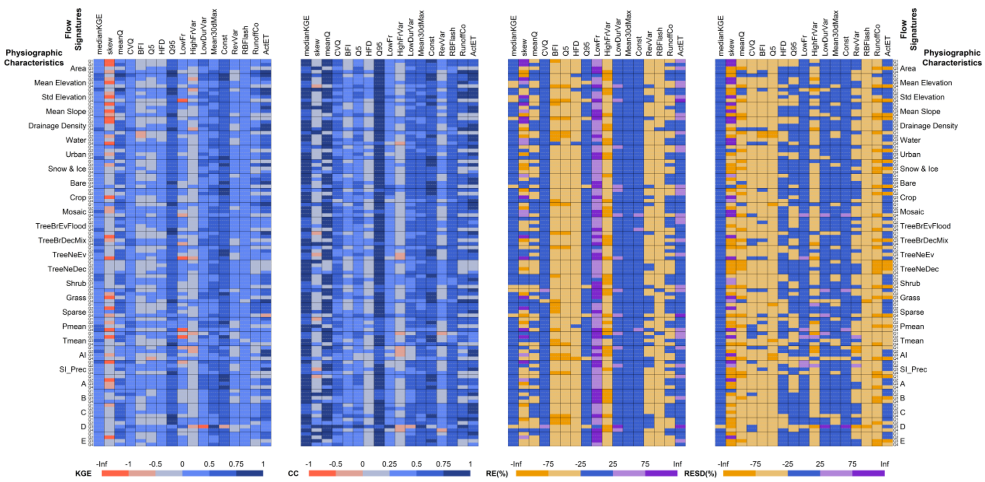

Figure 7. Matrix showing the relation between model capacity to capture flow signatures (colors, where blue is good and yellow/red/purple is poor performance) and physiography of catchments, divided into quartiles (Q1-Q4) for characteristics of the total area upstream each gauging station with more than 10 years of continuous data (5338 catchments). Description of flow signatures and physiographic characteristics are found in Table 4-5 and metrics used for model performance in Eq. 1-4.

5. Discussion

5.1 Potential for improvements

The results from evaluating model performance using several metrics, several thousand gauges and numerous flow signatures, gave clear indication on where the model most urgently needs improvements. The WWH model has severe problems with dry regions and base flow conditions, especially where the flow is sporadic (e.g. red areas in Fig. 5). These are difficult areas to model and they will need special analysis, so instead, we suggest starting with improvements that can be undertaken relatively quickly and easily. These mainly focus on the overall water balance.

Firstly, the global water balance can be improved through re-calibration but some basic concepts need to be adjusted accordingly: (i) more careful analyses indicate that the choice of climate regions based on Köppens classification for applying the different PET algorithms was not optimal and needs some adjustments, (ii) linking the centroid of the catchments to the nearest precipitation grid seems to remove a lot of the spatial variation and instead an average of nearest grids should be tried. Secondly, the HRUs can be recalibrated and reconsidered, and we suggest (i) testing a calibration scheme based on regionalized parameters rather than global, using clustering based on physiographic similarities (e.g. Hundecha et al., 2016), (ii) including soil properties in the HRU concept again (as in the original version of HYPE, see Lindström et al., 2010) to account for spatial variability in soil-water discharge linked to porosity in addition to vegetation and elevation. Thirdly,

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the behavior of hydrological features, such as lakes, reservoirs, glaciers, and floodplains can be evaluated and calibrated separately, after categorizing them more carefully or from individual tuning. Finally, more observations can be included, both in-situ by adding more gauges to the system and from global Earth Observation products, for instance on water levels and storage. Hence, each step in Fig. 3 still has potential for model improvements.

The stepwise parameter-estimation approach should ideally be cycled a couple of times to find robust values under new fixed parameter conditions. However, as the model was carefully evaluated during the calibration, there were a lot of bug fixing, corrections and additional improvements resulting between the steps and time was rather spent on this than on several full-filled iterations. Therefore, the stepwise calibration was subjected to several re-takes and shifts between steps until it successfully could full-fill all the calibration steps in one entire sequence (Fig. 8). Hence, only one loop was done for parameter estimations in this study. The procedure was judged as very useful for the model to be potentially right for the right reason, but also very time-consuming. However, applying a catchment modeler’s approach, this is inevitable for reliably integrated catchment modelling and both the step-wise calibration and iterative model corrections will continue with new model versions.

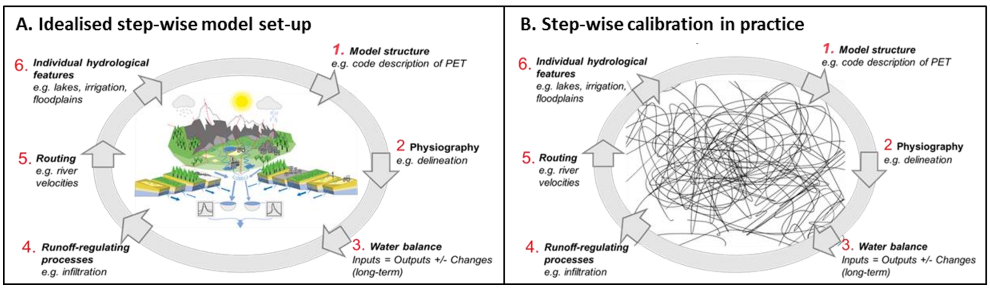

Figure 8. Discrepancy between the idealised procedure for step-wise calibration (A) and the numerous iterations between the steps that appear in reality (B), leading to overall model corrections.

5.2 Model usefulness

Catchment models are often applied by water managers and the usefulness is part of the concept. The analysis of WWH model performance shows that also this first version can to some extent be useful for water managers in several regions globally. For instance, long-term averages are rather reliable in Eastern USA, Europe, South-East Asia, Japan as well as most of Russia, Canada, and South America. Here the model could thus be used for e.g. analyzing shifts in water resources between different climate periods. For high flows, monthly values show good performance as well as the spatial pattern of relative values. This implies that the model could already be used for seasonal forecasting of recharge to hydropower reservoirs, for which these variables are often used. Accordingly, the model has been applied for producing water-related climate impact indicators and it is set-up operationally to provide monthly river-flow forecasts for 6 months ahead (http://hypeweb.smhi.se/).

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The model provides a first platform for catchment modelling to be further refined and experimented with at the global, regional and local scales. Parts of the model can be extracted (e.g. specific catchments or countries) and used as infrastructure, when starting the time-consuming process of setting up a catchment model. The model can then be improved for the selected catchments by exchanging the global input data with local data and knowledge, as well as parameters estimated to fit with local observations. Significant improvements in model performance from such a procedure have already been noted for West Africa (Andersson et al., 2017). In Sweden the operational HYPE model runs with national data and adjusted parameter values, providing an average daily NSE (Nash and Sutcliffe, 1970) of 0.83 for 222 stations with ≤5% regulation and an average relative volume error of ±5% for the period 1999–2008. For all gauging sites (some 400) with both regulated and unregulated rivers, the mean monthly NSE is 0.80. The Swedish HYPE model has been improved incrementally during more than 10 years and has proven very useful in providing decision-support to society. It supports a national warning service with operational forecasting of floods and droughts (e.g. Pechlivanidis et al., 2014), and the water framework directive for measure plans to improve water quality (e.g. Arheimer and Pers, 2017; Arheimer et al., 2015). Moreover, it has been used in assessments of hydro-morphological impact (e.g. Arheimer and Lindström, 2014), climate-change impact analysis (e.g. Arheimer and Lindström, 2015) and combined effects from multiple-drivers on water resources in a changing environment (e.g. Arheimer et al., 2017; Arheimer et al., 2018).

Thus, it is found very useful to have a national multi-catchment model to support society in water related issues. This should be encouraging for other countries who do not yet have a national model set-up and also for international river basin authorities searching for a more harmonized way to predict river flow across administrative borders. Using the WWH as a starting point would be a quick and low-cost alternative for getting started with more detailed catchment modelling for decision-support in water management. Parts of the model are therefore shared and can be requested at http://hypecode.smhi.se/. Using a common framework for catchment modelling by many research groups and practitioners will probably advance science as it enables a critical mass and better communication when sharing experiences. Only when using the same methods or data, there is full transparency in the research process so that scientific progress and failures can be clearly understood, shared and learnt from. The WWH could be one stepping stone in such a collaborative process between catchment modellers across the globe.

6. Conclusions

The catchment modelling approach applied (using the HYPE model, open global data and recent calibration techniques) resulted in better performance (median monthly KGE = 0.4) than what has been reported so far from more traditional gridded modelling of river flow at the global scale. Major variability in hydrological processes could be recognized world-wide using global parameters, as these were linked to physiographical variables to describe spatial variability and calibrated in a step-wise manner. Clearly, the community of catchment modellers can contribute to research also at the global scale nowadays with the numerous open data available and advanced processing facilities.

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However, the WWH resulting from this first model version should be used with caution (especially in dry regions) as the performance may still be of low quality for local or regional applications in water management. Geographically, the model performs best in Eastern USA, Europe, South-East Asia and Japan, as well as parts of Russia, Canada, and South America. The model shows overall good potential to capture flow signatures of monthly high flows, spatial variability of high flows, duration of low flows and constancy of daily flow. Nevertheless, there remains large potential for model improvements and it is suggested both to redo the calibration and reconsider parts of the model structure for the next WWH version.

The step-wise calibration procedure was judged as very useful for the model to be potentially right for the right reason, but also very time-consuming. The calibration cycle is suggested to be repeated a couple of times to find robust values under new fixed parameter conditions, which is a long-term commitment of continuous model refinement. The model set-up will be released in new model versions during this incremental improvement. For the next version, special focus will be given to the water balance (i.e. precipitation and evapotranspiration), soil storage and dynamics from hydrological features, such as lakes, reservoirs, glaciers and floodplains.

The model will be shared by providing a piece of the world to modellers working at the regional scale to appreciate local knowledge, establish a critical mass of experts from different parts of the world and improve the model in a collaborative manner. The model can serve as a fast track to a model environment for users who do not have this ready at hands and in return the WWH can be improved from feedback on hydrological processes from local experts across the world. Potentially it will accelerate scientific advancement if more researchers start using the same tools and data, which makes it easier to be transparent when evaluating and comparing scientific results.

Code availability

Hypecode.smhi.se

Data availability

Hypeweb.smhi.se

Appendices

The Table below show additional information to Table A1 regarding which HYPE parameters that were calibrated for each process during the model set-up and the range of resulting parameter values. Description of each parameter can be found in the HYPE wiki at http://hypeweb.smhi.se/.

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Table A1. Metrics and parameter values from the stepwise parameter-estimation globally. Parameter names and values are given in the same order of appearance (columns 2 and 6).

Hydrological Process	**HYPE parameters** http://hypecode.smhi.se/	**No. gauges**	**Median value of metric(s)**		**Parameter value(s)**
			Before	**After**	
Potential Evapo-Transpiration (3 PET-algorithms: median of ranges constrained with MODIS)	Jhtadd, jhtscale, kc2, kc3, kc4, krs, alb, alfapt	0	RE: 11.5 %	RE: 0.5%	5; 100; [0.7-1.7]; [0.15-1.7]; [0.8-1.6]; 0.16; [0.3-0.8]; 1.26
Glaciers (only evaluated vs mass balance data)	glacvexp, glacvcoef, glacvexp1, glacvcoef, glac2arlim, glacannmb, glacttmp, glaccmlt, glaccmrad, glaccmrefr, glacalb, fepotglac	296	RE: 0.38% CC: 0.51	-	1.38, 0.17 1.25, 12.88 25 000 000, 0, 0, 1.58, 0.19, 0.06, 0.35, 0
Soils (average, rock, urban, water, rice)	5 soils: rrcs1, rrcs2, rrcs3,trrcs, mperc1, mperc2, macerate, mactrinf, mactrsm, srrate, wcwp, wcfc, wcep	25	RE: -14.1% KGE: 0.2		Ranges: [0.20 - 0.5]; [0.01 - 0.45]; [0.01 - 0.1]; [0.05 - 0.35]; [30 – 100]; [10 - 60]; [0.05 – 0.7]; [12 - 30]; [0.3 – 0.9]; [0.01 – 0.3]; [0.01 – 0.6]; [0.2 – 0.6] ; [0.01 – 0.5]
Bare soils in deserts (calibrated manually)	rrcs1, rrcs2, rrcs3, trrcs, mperc1 mperc2, wcwp1, macerate, mactrinf, mactrsm, sfrost, srrate, wcwp1, wcwp2, wcwp3, wcfc1, wcfc2, wcfc3, wcep1, wcep2, wcep3	4	RE: 236.1%	RE: -18.9	0.6, 0.3, 0.0002, 0.15, 10, 0.1, 10, 0.8, 1, 0.01, 0.01, 0.0001, 0.0001, 0.3, 0.3, 0.0001, 0.03, 0.03, 0.0003
1. Precipitation: catchment elevation	Pcelevth, Pcelevadd, Pcelevmax	147	RE: -6.7%	RE: 4.4%	500; 0.01; 0.7
2. Precipitation: land-cover altitude	5 elevation zones: pcluse	1041	RE: 24.3%	RE: 10.1%	0.05; 0.2; 0.25; 0.25; 0.35
3. HRUs in areas without snow	10 HRUs: kc2, kc3, kc4, alb, soilcorr, srrcs, soilcorr	318	KGE: 0.16	KGE: 0.27	Range: [0.90-1.54]; [0.40-1.77]; [0.20-1.90]; [0.20-0.80]; [1.00-10.55]; [0.03-0.50];

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4. HRUs in areas with snow: ET, recession and active soil depth	10 HRUs: ttmp, cmlt, cmrad, fscdist0, fepotsnow	225	KGE: 0.16	KGE: 0.24	Ranges: [-2.67-1.80]; [1.10-4.00]; [0.16-1.5]; [0.20-0.75]; [0.09-0.98]
5. Upstream lakes	Ilratk, ilratp	731	CC: 0.71	CC: 0.72	1.8; 1.4 (depth: 5 m; icatch: 0.3)
6. Regionalised ET (in 12 Köppen climate regions)	12 climates: cevpcorr	458	KGE: 0.58	KGE: 0.62	Ranges: [-0.43 – 0.38]
7. River routing	rivvel, damp	302	CC: 0.70	CC: 0.71	0.6; 1.0
8. Lake rating curve	888 Lakes: rate; exp (LakeData.txt)	945	CC: 0.50	CC: 0.59	Ranges: [0.001– 1013]; [1.002 – 3.0];
9. Floodplains (partly calibrated manually)	13 Floodplains: rclfp; rclpl; rcrfp; rcfpr (FloodData.txt)	32	KGE: -0.03	KGE: 0.03	Ranges: [0.05 – 0.99]; [0.15 – 0.90]; [0.05 – 0.99]; [0.15 – 0.90]
10. Evaporation from water surface	$kc2_{water}$, $kc3_{water}$, $kc4_{water}$	201	RE: -20.7%	RE: -12.2%	1.36; 0.65; 1.25
11. Specific lake evaporation	2 regions: cevpcorr	16	RE: 24.8%	RE: 4.8%	Ranges: [0.375-0.5]

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