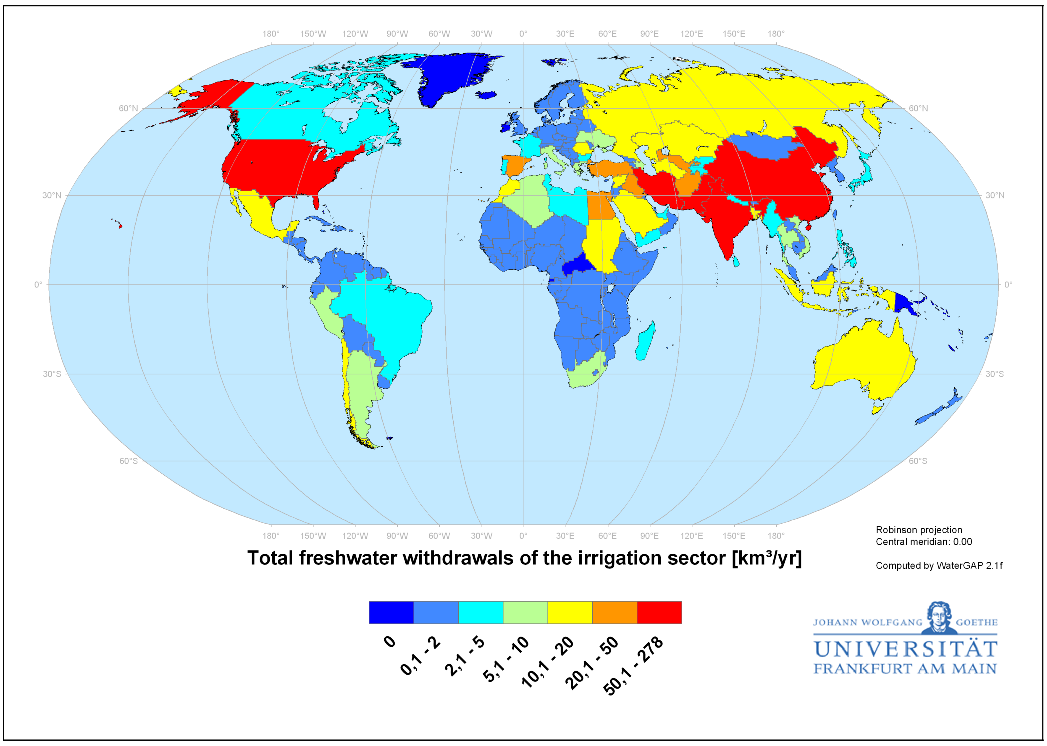
Technical Report No. 34

IMPROVEMENTS IN HYDROLOGICAL PROCESSES IN GENERAL HYDROLOGICAL MODELS AND LAND SURFACE MODELS WITHIN WATCH.



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WATCH is an Integrated Project Funded by the European Commission under the Sixth Framework Programme, Global Change and Ecosystems Thematic Priority Area (contract number: 036946).
The WACH project started 01/02/2007 and will continue for 4 years.

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Introduction

During the 4 years of WATCH the participating land-surface models progressed in their description of the continental water cycle. The following 5 models participating in WATCH have been developed further in the course of the project :

- JULES : Joint UK Land Environment Simulator,
- ORCHIDEE : ORganizing Carbon and Hydrology In Dynamic EcosystEms,
- LPJ : Lund-Postdam-Jena Dynamic Global Vegetation Model,
- WATERGAP : University of Frankfurt global hydrological model
- VIC : Variable infitration Capacity model.

The main focus of the development of these models in the last 4 years were the impact of human activities on the continental water budget. It is the comparison with global hydrological models during WATCH (Hadelland et al, 2011) that lead the land surface modelling groups to the conviction that the anthropogenic pressure on the water cycle was a major element missing in their models.

At the start of the project only ORCHIDEE could simulate the impact of irrigation and now most of them represent this process. LPJ and Jules also introduced the representation of reservoirs and dam while it could be demonstrated in ORCHIDEE that the lack of this process leads to major errors in the simulation of irrigation. Finally VIC undertook a pioneering development by introducing water temperature into the routing scheme of the model. This will allow in the future to predict the evolution of the temperature of water bodies. An impact of climate change which will have important consequences for the ecology and industrial use of water bodies.

With WATCH some of the land-surface models introduced for the first time the impact of human activities on the continental water cycle. But in the years to come these aspects will be the main focus of land-surface model developments as we barely scratched the surface in this project. Once the water volumes are well represented and all the human abstractions taken into account, the water temperature and biochemical composition will become major topics. Other components of the Earth system models, the ocean models in particular, will require this information in order to close the global cycle of the water and carbon.

Evolution of JULES

Irrigation

The standard JULES model represents 9 land surface types (including 5 vegetation types) within a gridbox and models the energy balance of each type separately using a "tile" approach. However, all surface types have access to the same soil moisture stores – there is no subgrid variability of soil moisture. As irrigation rarely covers an entire gridbox (0.5° in the WATCH Forcing Data), this lack of subgrid variability meant that the standard JULES could not simulate irrigation of agricultural land.

An irrigation model was incorporated into JULES by providing two sets of soil moisture stores (each with 4 layers) in each gridbox, to represent irrigated and non-irrigated areas separately. Assuming there is sufficient water available, the soil moisture in the irrigated area is "topped up" to the critical point (the point at which vegetation is no longer water stressed) once a day. The evaporation from the irrigated area is then approximately equal to the potential evaporation. As JULES does not model crop growth, a crop calendar was also included by adapting the approach of Döll and Siebert (2002). Crops are considered to grow when and where simple temperature- and precipitation-based criteria are met. At present we only allow one cropping season per year. Irrigation is applied only during the growing season. The global average net irrigation amount for 1986-1995 simulated by JULES was 1269 km3 yr-1, which compares reasonably with the estimate of 1092 km3 yr-1 from Döll and Siebert (2002). There was similarly good agreement with the country-level values from Döll and Siebert (2002).

Reservoirs and dams

JULES simulates the flow of water through a river network using the TRIP linear model of Oki et al. (1999), but the standard model ignores the effects of dam and reservoir operations. A new parameterization of dam operation was added, largely following Biemans et al. (2011). The model is built around a set of simple rules that calculate the amount of water released from a dam as a function of the demand for water from downstream areas and the amount of water stored in the reservoir behind the dam. Each dam is considered to be either primarily for irrigation supply or for "other" purposes, and separate rules govern the operation of each type. The location and characteristics of dams are taken from the Global Reservoir and Dam (GRanD) database (Lehner et al., 2011). At each gridbox the demand for irrigation water is calculated on a daily basis (using the irrigation scheme outlined above) and the model tries to meet this demand, first by extracting water from the local river, then if necessary augmenting this with water from a dam release. Each dam also has to try to maintain a minimum flow in the river for environmental purposes. If insufficient water is available for irrigation, the water supplied cannot meet demand and the crops will start to experience water stress. This parameterization of the effects of reservoir and dam operation in JULES is currently being tested, but early results are promising with improved representation of flows in rivers that are highly regulated by dams.

The addition of these representations of irrigation demand and water supply from rivers and reservoirs is a major advance in the JULES model. The model is now more appropriate for use in studies of water resources, in particular of how the availability of water will change as the demand for water for agriculture increases over the coming century.

Evolution of ORCHIDEE

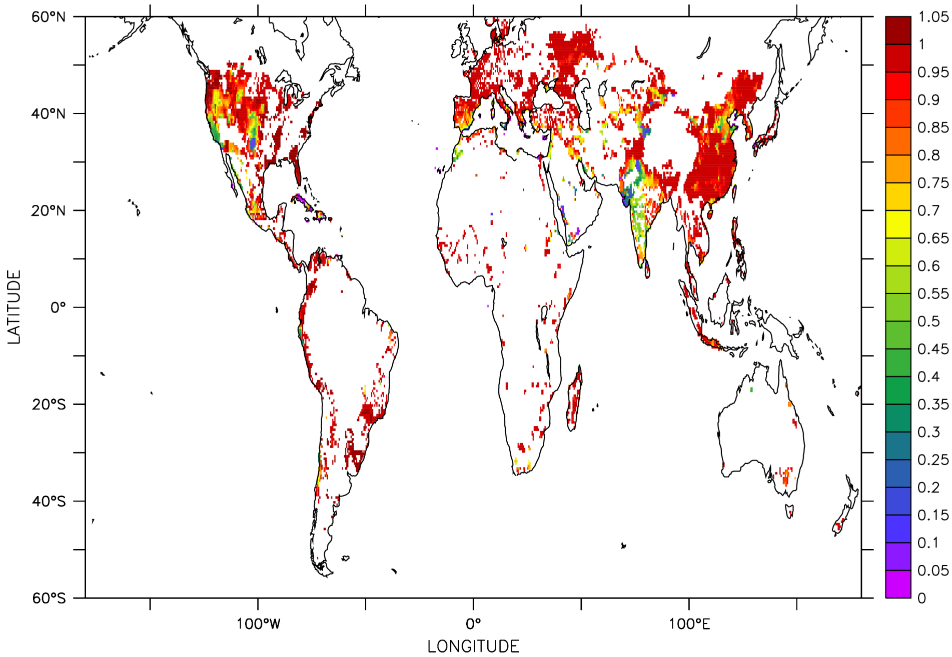
Validation of the irrigation parametrization

The irrigation parametrization has been implemented in ORCHIDEE since 2002 (de Rosnay et al. 2003). The multiple soil-reservoir approach of ORCHIDEE makes it possible to apply the irrigation only the mesh fraction covered by irrigated crops.Up to now the estimation of the required irrigation was based on the FAO formulation. It gave unsatisfactory results as the seasonal cycle of the irrigation requirement was not correct and inconsistent with the state of the vegetation simulated by ORCHIDEE.

It was decided to replace this by a new formulation based on potential transpiration. This means that the irrigation which will be taken from the streams will be based on the moisture stress felt by the plants for the transpirations only. This means that the irrigation requirement will automatically follow the annual cycle of transpiration and thus take into account the state of the vegetation or the crops. This takes more directly advantage of all the elements describing the state of the vegetation in ORCHIDEE than the old FOA formulation did.

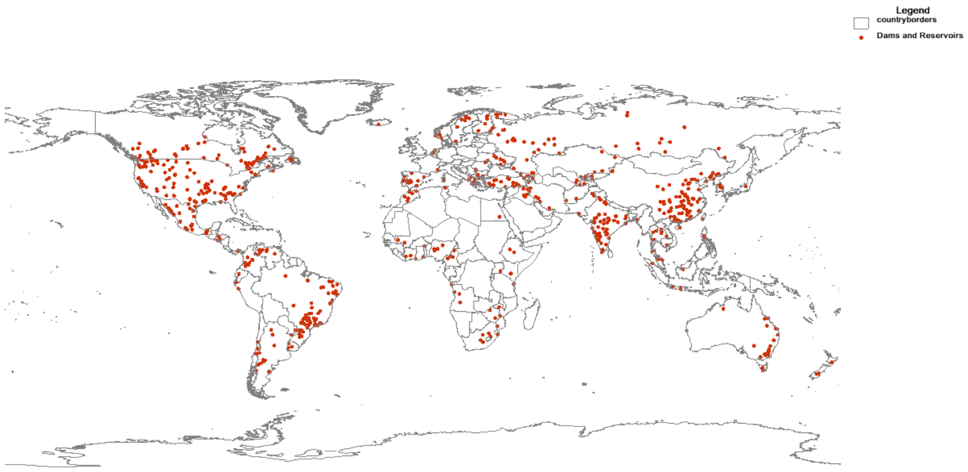
This new formulation was tested and its impact on the global irrigation estimates evaluated. The detailed analysis of this evolution of ORCHIDEE is published in the thesis of Matthieu Guimberteau.

Using the ORCHIDEE with the 50km resolution forcing also revealed another issue which has to do with the source of the water used for the irrigation. In the coupled environment, i.e. with typical GCM resolutions, in each grid box we could find a river large enough to support the irrigation needs. At 50km this was not possible anymore and many areas having irrigated crops were not irrigated by the model. We thus had to extend the algorithm to allow the model to look for water in the rivers in the 8 neighboring grid boxes.



Map of the ratio irrigation/irrigation requirement showing (for values lower than 0.8) the areas where insufficient water availability limits the actual irrigation.

The figure above shows that the model has the largest difficulties to fulfill the irrigation requirements in the Western part of the Indian peninsula. We looked for the possible cause and the most likely cause is the lack of dams and reservoirs in the models. The map below shows that most regions where the model cannot fulfill the irrigation requirements have a large density of dams and reservoirs. It seems that in these regions without large rivers the farmers will create this infrastructure to keep the water of smaller river to satisfy their water needs for irrigation.



Map of dams and reservoirs

This indicates that before operating the irrigation parametrization at higher resolution in ORCHIDEE we will need to introduce dams and reservoirs. A major development effort is needed.

Operational use of the CWWR hydrology

The 11 layer CWRR moisture scheme in ORCHIDEE has been applied here for the first time at the global scale. Before it has been validated in detail in over the West African region (d'Orgeval et al, 2008). Some minor corrections to the model were needed in numerical aspects. The physics of the model behaved well in all regions of the globe as could be demonstrated by a detailed validation of the fluxes and in particular the river discharges. A comparison with the simpler Choisnel scheme, which is standard in ORCHIDEE (de Rosnay and Polcher, 1998), demonstrated that CWRR performed better for the mean annual cycle and inter-annual variability. The behavior of both models in the hydrological extremes, mostly droughts, is still under investigation.

Evolution of LPJ

Within the WATCH project (and in collaboration with other projects), the LPJmL dynamic global vegetation and water balance model has been improved considerably in terms of the representation of hydrological processes. These model upgrades were required for the later model runs performed in WATCH and WaterMIP, since at the start of the project only a pilot version of the former LPJ model upgraded by agricultural modules existed (as described in detail by Bondeau et al. 2007). That model version was in need of improvements in terms of better representation of individual crop types and their spatio-temporal distribution, and especially in terms of the representation of irrigated crops and associated river routing and water storage pools. As concerns the latter, we developed a river routing module operating at 0.5° resolution in combination with a fully dynamic irrigation and a reservoir management scheme.

Representation of crops and irrigation in LPJmL

The pre-existing irrigation module in LPJmL (Bondeau et al. 2007) has been substantially refined within the first year of the WATCH project, and a detailed description of the new model along with first applications have been published in its second year (Gerten et al., 2008; Rost et al., 2008a,b). The first model implementation assumed irrigation on areas equipped for irrigation, irrespective of whether enough water is available in the respective locations (0.5° grid cells) and using a simple irrigation module only (Bondeau et al. 2007). In WATCH, we implemented a new irrigation scheme with the following (new or improved) features – all as detailed in Rost et al. (2008a):

- Accumulation (along the river network) of runoff generated in upstream grid cells – i.e. river routing –, at daily time steps
- Refined calculation of crop water limitation as a function of atmospheric water deficit, soil moisture and plant hydraulic traits
- Option to withdraw water from the river system and from lakes, reservoirs and groundwater on areas suited for irrigation (following Siebert et al. 2007 and in a later version Portmann et al. 2010) in the case of crop water limitation and application of this water to the field
- Accounting for country-specific conveyance water losses and application water losses (i.e. irrigation efficiencies, taken from Rohwer et al. 2007)
- Possibility to distinguish between withdrawal of local and renewable water (in simulations that consider only these resources) and additional withdrawal from fossil groundwater and from water available through river diversions (assuming that crop water needs are always fulfilled)
- Differentiation of those “blue” water contributions and the “green” water contributions (directly from rainfall) on irrigated areas.

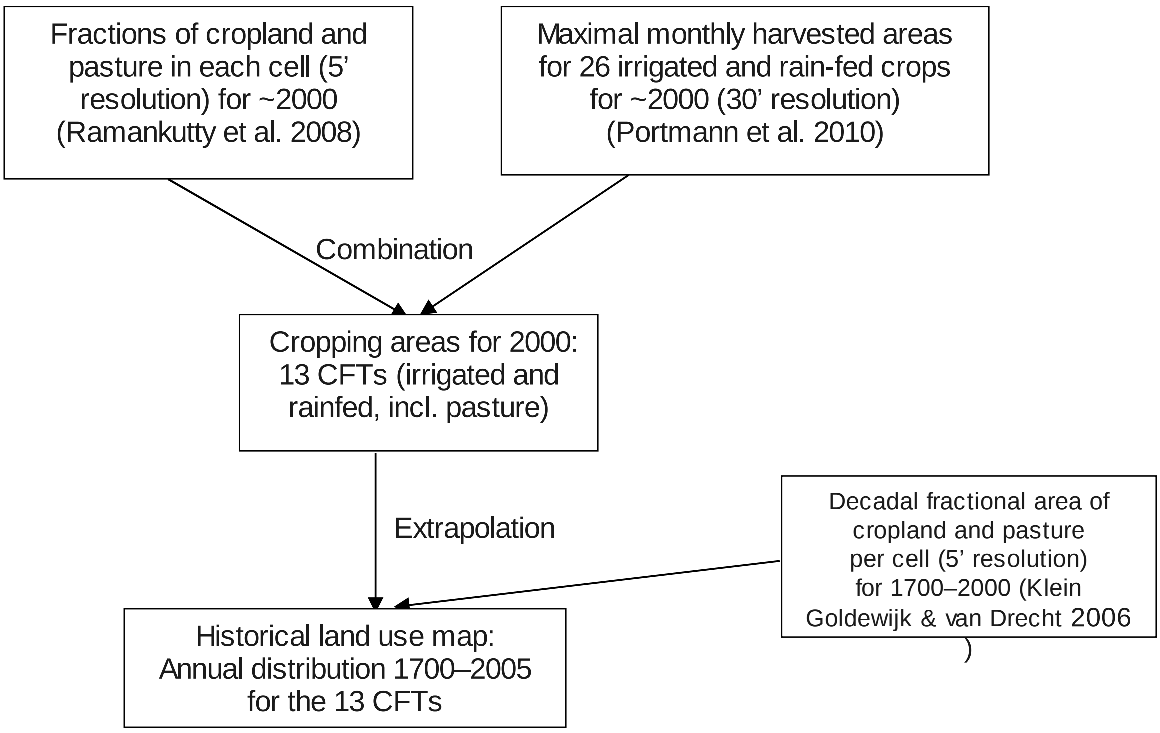
These improvements were a core prerequisite for a number of studies performed within WATCH, as follows.

- First – apart from the overall improvements of simulated crop yields and crop water use achieved (cf. Fader et al. 2010) – they allowed for a clear distinction of the individual contributions of irrigation and land use change as opposed to the contributions of climatic and CO2 changes to observed changes in worldwide river discharge over the past century (see Gerten et al. 2008).
- Second, they allowed for robust and process-based quantification of the share of green water in global agricultural water consumption (about 90%; Rost et al. 2008) and, thus, the share of green water in countries’ water footprints (through both country-internal water consumption and imports via virtual water trade; Fader et al. 2011).
- Third, the improved LPJmL model contributed to the model intercomparison of global hydrological and land surface models as for the 20th century water cycle (Haddeland et al. 2011); that study did not check systematically whether the achieved model improvements

improved the simulation quality, but the fact that LPJmL results are well placed within the model ensemble demonstrates that a dynamic global vegetation model including agriculture performs at least as good as other, stand-alone hydrology models. This has also been shown by the studies of Jung et al. (2010) who investigated using a number of models and data sources recent trends in global land evapotranspiration; of Hagemann et al. (2011), who projected runoff and evapotranspiration changes into the 21st century using a set of global hydrology and land surface models and bias-corrected climate change projections; and of Gudmundsson et al. (2011) who are examining model fitness in terms of reproducing runoff quantiles in small, undisturbed European river basins. The enhanced LPJmL model was also used in a pilot assessment of climate change impacts on runoff from about 20 AOGCMs (Heinke et al. 2009).

Improvement of crop parameterisations and implementation of new land use dataset in LPJmL

In WB1 we incorporated a new land use dataset into the LPJmL model. The main feature of this dataset is that is for the first time consistently combines irrigated and rainfed crop areas for the 12 major crop types of the world (taken from Portmann et al. 2010), allowing for an even more refined distinction of blue and green water shares in both space and time, and allowing for an overall better representation of agriculture in a global hydrology and biosphere model such as LPJmL. In addition to the above-mentioned studies, several applications were performed that especially relied on the new land use dataset and related refined parameterisations (global quantifications of crop water use per biomass unit, i.e. virtual water contents, and resulting country water footprints; done together with WB6 and another project) as documented in two scientific papers (Fader et al. 2010, 2011). A schematic overview of the input data organisation for this renewed model is given in the below figure (taken from the Appendix of the Fader et al. 2010 study).



Compilation procedure of the new land use dataset for LPJmL ("CFTs" = crop functional types).

This new land use dataset was the prerequisite for up-to-date assessments of the above-cited studies (see “Representation of crops and irrigation in LPJmL”) and also for a study on effects of climate, population and diet change on agricultural green and blue water requirements (Gerten et al. 2011), conducted in WATCH’s WB6.

Representation of dams and reservoirs in LPJmL

In order to make a realistic estimate of the total surface water available for agriculture, it is important to account for the water supply from artificial reservoirs. Therefore, we implemented a reservoir management scheme in LPJmL. This reservoir management scheme introduces around 7000 reservoirs dynamically in the river routing scheme. Specific reservoir operation rules were developed for irrigation reservoirs and other reservoirs (hydropower, navigation, flood control). Besides simulating the change in timing of riverflow, it also simulates extractions of irrigation water and supply to irrigated area downstream of the reservoir. Therefore, it allows for a spatially explicit quantitative estimate of the water withdrawal and supply from reservoirs.

The implementation of the reservoir scheme, including its validation and , are described in a scientific publication . Main conclusions were:

- Reservoirs have significantly changed the timing and amount of rivers discharging into the ocean.
- An analysis of simulated discharge at 304 gauging station locations with reservoirs upstream showed an improvement of the RMSE in 91% of the cases.
- By storing and redistributing water, reservoirs have significantly increased the surface water availability in many regions of the world.
- Continents gaining the most from their reservoirs are North America, Africa, and Asia, where reservoirs supplied 57, 22, and 360 km3 yr−1 respectively between 1981–2000, which is in all cases 40% more than the availability in the situation without reservoirs.
- Globally, the irrigation water supply from reservoirs increased from around 18 km3 yr−1 (adding 5% to surface water supply) at the beginning of the 20th century to 460 km3 yr−1 (adding almost 40% to surface water supply) at the end of the 20th century.

The improved representation of reservoir management in LPJmL is useful in WATCH WB6 model intercomparison study, where one of the studies looks at the representation of the human interactions in the global hydrological cycle.

Further, the LPJmL reservoir scheme is applied in a study conducted in WB6 under ‘water for food’ assessements, in which we calculate the consequence of water shortage on food production at the end of the 21st century.

Evolution of MPI

The dynamical wetlands extent scheme

In the framework of WATCH a PhD research was conducted to develop a dynamical wetlands hydrology scheme. This scheme accounts for changes in the wetland surface area caused by variations in climate conditions.

Wetlands have a strong impact on the hydrological cycle as they increase evapotranspiration, store surface water and regulate river flow. However, in most Earth System Models and Global Hydrological Models the wetland extent is constant in time. The dynamical wetland extent scheme (DWES) now provides the possibility to study the effects of changing climate on the distribution and extent of wetlands as well as their feedbacks to climate on a global scale.

In order to provide a suitable environment for the DWES two separate models, the Simplified Land Surface Scheme and the Hydrological Discharge Model, were coupled. Their combination now forms the MPI Hydrological Model (MPI-HM) with the dynamical wetland scheme providing the interface between both sub-models. The sub-models were supplemented with discrete wetland water storages and all land surface water fluxes were separated into wetland and non-wetland related water flows. A new water balance calculation was implemented for the wetland part of the model grid cells. Additionally, a new approach was developed to relate the calculated change in wetland water volume with the change of its surface area based on the sub grid distribution of slope within the grid cells. This approach required boundary data of slope statistics which were derived from highly resolved topographical data.

Furthermore, it was necessary to optimize global parameters for the wetland water flow velocity coefficient, the inflow scheme and the sensitivity of area change to slope distribution. This was done using an alternative version of the MPI-HM which relies on a constant wetland distribution. This static MPI-HM was constrained with four different wetland observation datasets. The simulated catchment integrated river flow could be compared between the static and the dynamical wetland MPI-HM versions to derived the optimized parameters.

The dynamical wetland scheme was validated against global wetland observations, observations of wetland extent seasonality and water level variations. It was shown to perform best in the northern hemisphere. Here, the spatial and temporal correlation of wetlands is high and the overall wetland fraction agrees with the observed ones. Likewise, the southern hemisphere shows a high correlation but there the overall wetland extent is overestimated.

Further information about the dynamical wetland scheme is found in Stacke,T. 2011. Development of a dynamical wetlands hydrology scheme and its application under different climate conditions. PhD Thesis, Max Planck Institute for Meteorology, Hamburg, submitted.

The irrigation scheme in the MPI-HM

The WaterMIP project included the simulation of human impacts on the hydrological cycle. Thus, a simple irrigation scheme was implemented into the MPI-HM. Based on a monthly map of irrigated area, the irrigation scheme ensures a soil moisture content above the wilting point for the irrigated area fraction. In this fraction plants may transpire at their potential rate. The irrigation scheme demanded some structural changes in the MPI-HM like additional input and output fields. Furthermore, this task profited heavily from the development work for the dynamical wetland scheme. Due to the already coupled SL and HD Models the irrigation scheme is able to extract the irrigation water from nearby simulated river channels. Simulations with the irrigation scheme showed a significantly increased evapotranspiration focusing mostly on Northern India. The impact on the river flow simulations resulted in improvements for a small number of river catchments only. While the water flow during the irrigation period was decreased, it was generally still higher than observed.

The irrigation scheme in JSBACH

Workblock 5 required coupled land-atmosphere simulations with and without irrigation to assess the impact of irrigation on the state of the atmosphere. Thus, the land component of the MPI Earth System Model JSBACH was supplemented with an irrigation scheme similar to the one in the MPI-HM.
However, the more complex structure required the implementation of an extra land surface tile for irrigated crops as well as the introduction of a separated field to manage the irrigation water gift. Otherwise JSBACH would distribute the additional soil moisture equally over all tiles thus ignoring the allocated irrigation grid cell fraction. Furthermore, the JSBACH crop distribution map had to be adapted to be consistent with the map of irrigated area.
Although the effect of the irrigation scheme was statistically significant on almost the whole land surface, it only plays a distinctive role in Northern India. In most other areas the irrigation signal was much lower than the simulated climate variability.

General improvements of the MPI-HM

In order to contribute to the WATCH project several general changes in the setup and structure of the MPI-HM were necessary. The number of MPI-HM output variables was increased and an additional routine was implemented to generate fields of monthly means. The model and its boundary fields were modified to accept the WATCH land sea mask and the DDM30 river direction field.
A very important model improvement was the implementation of water balance checks in several subroutines. Thus a number of smaller errors could be corrected in the former MPI-HM version.
Test simulations after the different model modifications showed a constant improvement of model results.

Evolution of WATERGAP

Evolution of the ground water model

The University of Frankfurt has continued the development of the ground water module in WATERGAP using statistics for different water use sectors. They have also compared their approach to those used in other hydrological model and land-surface models.

Limitations to the groundwater recharge that is currently represented in the WaterGAP model have been identified and the scheme is being further improved. The following gives the details of the current scheme and the improvements that are being made.

Groundwater recharge is currently represented in the WaterGAP model using a heuristic approach. In the standard version, groundwater recharge R_g is computed with a spatial resolution of 0.5° and daily time steps. This is done taking into account relief, soil texture, hydrogeology and the occurrence of permafrost and glacier:

$$R_g = \min(R_{g\max}, f_g R_l) \quad \text{with} \quad f_g = f_r f_t f_a f_{pg} \qquad (1)$$

R_{gmax} = soil texture specific maximum groundwater recharge [mm/d]

R_l = total runoff of land area [mm/d]

f_g = groundwater recharge factor ($0 \leq f_g < 1$)

f_r = relief-related factor ($0 < f_r < 1$)

f_t = texture-related factor ($0 \leq f_t \leq 1$)

f_a = aquifer-related factor ($0 < f_a < 1$)

f_{pg} = permafrost/glacier-related factor ($0 \leq f_g \leq 1$)

(Döll et al., submitted)

For figure 1, WaterGAP 2.1f was run with the following two input data sets of precipitation for the years 1961 to 1990:

1. Climate Research Unit (CRU), University of East Anglia, UK. CRU precipitation data: monthly values available for the period 1901 to 2002, spatial resolution 0.5
2. Global Precipitation Climatology Centre (GPCC), National Meteorological Service (DWD), Germany. GPCC precipitation data: monthly values available for the period 1951 to 2004, data are completed subsequently. Spatial resolution 0.5. Until 2004 full dataset available, from 2004 to 2006 only monitoring product available.

In the figure mean groundwater recharge of the CRU and the GPCC forced model runs is shown.

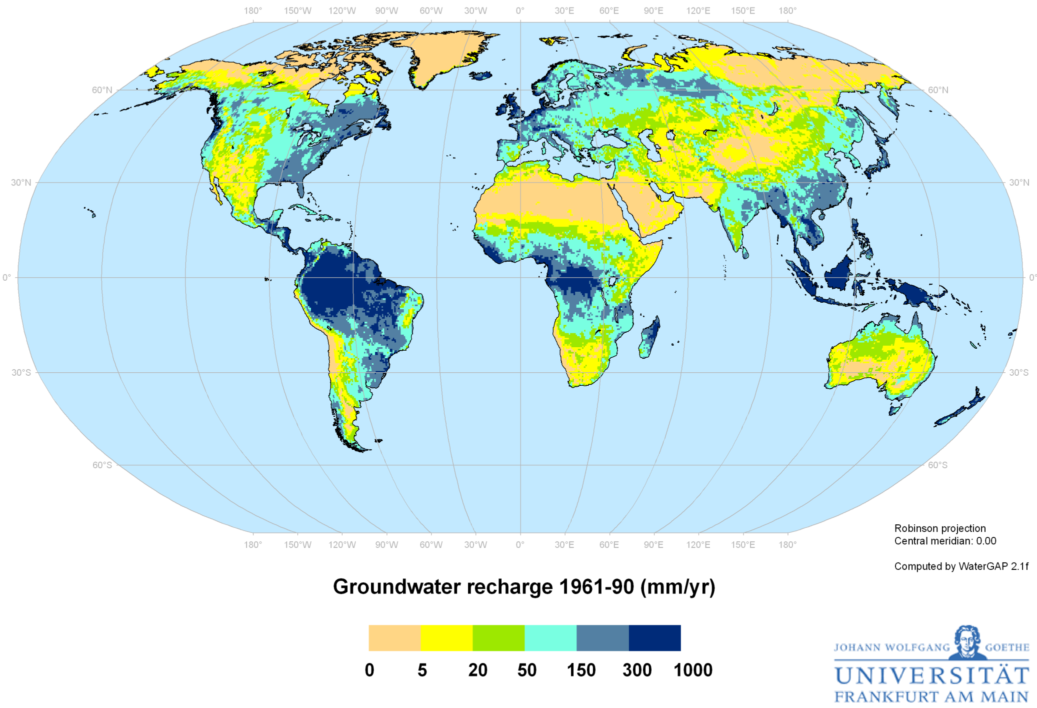


Figure 1: Groundwater recharge (mm/yr) as computed with WaterGAP 2.1f, mean value of CRU and GPCC precipitation forced model runs

The WaterGAP groundwater recharge algorithm will be further improved after a comparison with 51 independent estimates of groundwater recharge, it turned out not to work satisfactorily in arid and semi-arid regions (Döll et al., submitted). The authors found out that observed groundwater recharge below 20 mm/a was overestimated in (semi-) arid regions. Thus, as a first adjustment, for (semi-) arid grid cells groundwater recharge only takes place now in the model if daily precipitation exceeds 10 mm.

The following further model development approaches are currently under discussion:

- integration of depth of groundwater table
- integration of artificial drainage
- integration of preferential flow

Further improvement of the recharge algorithm will be based on the data and findings of Scanlon et al. (2006) and Jankiewicz et al. (2005). Additionally, Richard Taylor (University College London) estimated groundwater recharge in the humid tropics of Africa using groundwater-level fluctuations and soil-moisture balance modelling, base flow discharge and distributed groundwater flow models. Besides that, a catchment scale recharge model will be applied in humid areas of Bangladesh and China soon.

Scanlon et al. (2006) provide a collection of about 140 local recharge studies in (semi-) arid regions. Besides from the actual recharge value and the method used to obtain it, additional information on the study locations is given: number of sites at the location, area investigated, precipitation, soil and land cover information. Groundwater recharge as modelled by WaterGAP 2.1f was compared to these data with the aim to identify weaknesses of the current modelling approach.

For the comparison the following data sets were used:

- WaterGAP 2.1f: mean recharge of a model run using GPCC precipitation input and another one using CRU precipitation input. Despite the fact that for single study locations modelled groundwater recharge varies between 0.24 mm/ yr and 54.26 mm/yr between the two model runs due to the precipitation input, the correlation coefficient between the two model runs for groundwater recharge is 0.94 while the coefficient of determination (r^2) is 0.87.
- Local recharge studies: if several methods for recharge observation were used at the same study site, they were integrated separately in the data base. Thus, we derived 203 data base entries for groundwater recharge from the 140 study locations contained in Scanlon et al. (2006).

Analysing the data set, it was found that modelled and observed recharge values do not correlate (r^2=0.002, model efficiency= -0.005), which can also be taken from figure 2.

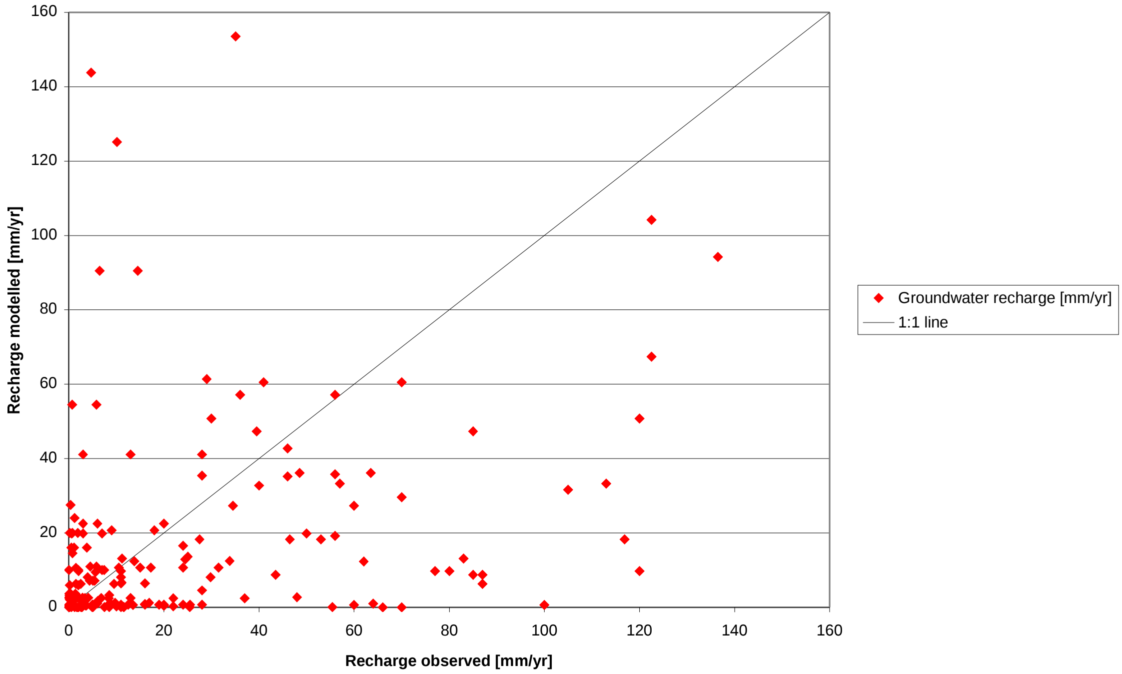


Figure 2: Comparison of recharge observations and recharge as modelled by WaterGAP 2.1f

To examine the reasons for the misfit, the additional information given by Scanlon et al. (2006) was integrated into the analysis. The study locations were grouped according to their characteristics and then again the correlation between observed and modelled recharge was computed.

Observation method: Correlation coefficients vary between 0.06 (modelling) and 0.98 (GIS). GIS, Chloride Mass Balance (saturated zone) and 14C tracer method show the highest correlation coefficients, but only 3 observations were available for GIS and only 5 were available for 14C. However, model results correspond well with the 23 observations using Chloride Mass Balance (saturated zone).

Area: It is not surprising that the model produces best results for larger areas, since its spatial resolution is 0.5° (corresponding to an area of 2 500 km² per grid cell at the equator). R^2 is very good (0.92) for the class 6 840 to 47 000 km²). But most of the available recharge studies concentrate on study areas below 1 000 km² where no correlation can be stated between model and observation results. Model results for the class >80 000 km² are generally too low, but only 6 observations are available here.

Precipitation: Only if precipitation is in the medium range (380 to 1 000 mm/year) a low correlation can be found between observed and modelled groundwater recharge. Modelled recharge does not fit to the observed one if there is either very little (below 380 mm/year) or very much (above 1 000 mm/year) rainfall. To be able to draw a conclusion out of the correlations, it was necessary to compare the precipitation input data of WGHM and the observed precipitation data at the study locations. Precipitation data used as model input and observed precipitation show a fair correlation of 0.40. Thus, it can be concluded that the missing recharge correlation at very low or very high precipitation location is not only due to disagreeing precipitation. Model algorithms seem to miss attributes which are relevant for recharge processes if there is particular low or high precipitation.

Soil: Recharge under sandy soils is modelled rather too low than too high. This is particularly true for fine sand. Thus, it can be hypothesised that if soil texture is coarser, the recharge modelled by WaterGAP gets worse compared to observations. The soil texture related groundwater factor in the recharge algorithm will be changed in a way that it better considers recharge processes under sandy soils in (semi-) arid regions.

Land cover: R^2 varies between the different land cover classes, but there is no clear picture what the reasons for the variations are. One reason for that is the small group sizes in the single land cover classes (3 to 14 observations). Classes of less than 3 observations were not taken into account. Good correlations can be stated for the no vegetation class (1), and also for the classes bush (7), dryland agriculture (9), mallee (13), and various vegetation (20). All classes but the grassland class are very small, thus, interpretation is difficult.

The conclusions of the data analysis will be considered for the improved groundwater recharge algorithm in WaterGAP.

Groundwater withdrawals

A global dataset of groundwater withdrawals for the sectors irrigation, household and manufacturing is currently set up at UF. The dataset is based on statistical information for sub-national units (e.g. districts, counties, river basins), wherever applicable. Data sources are national census surveys, recent book publications, research reports or other available information. Data which already (as of January, 2008) have been collected can be taken from figure 3. In a next step, the statistical information will be downscaled to the 0.5 model grid in order to perform a grid-based comparison of renewable groundwater resources and withdrawals. The total freshwater withdrawals calculated by the WaterGAP model for the sectors irrigation (figure 4, showing mean freshwater withdrawals for the period 1990-2002, to which most of the statistical information on groundwater withdrawals refers to), household and manufacturing can then be split up into surface water withdrawals and groundwater withdrawals.

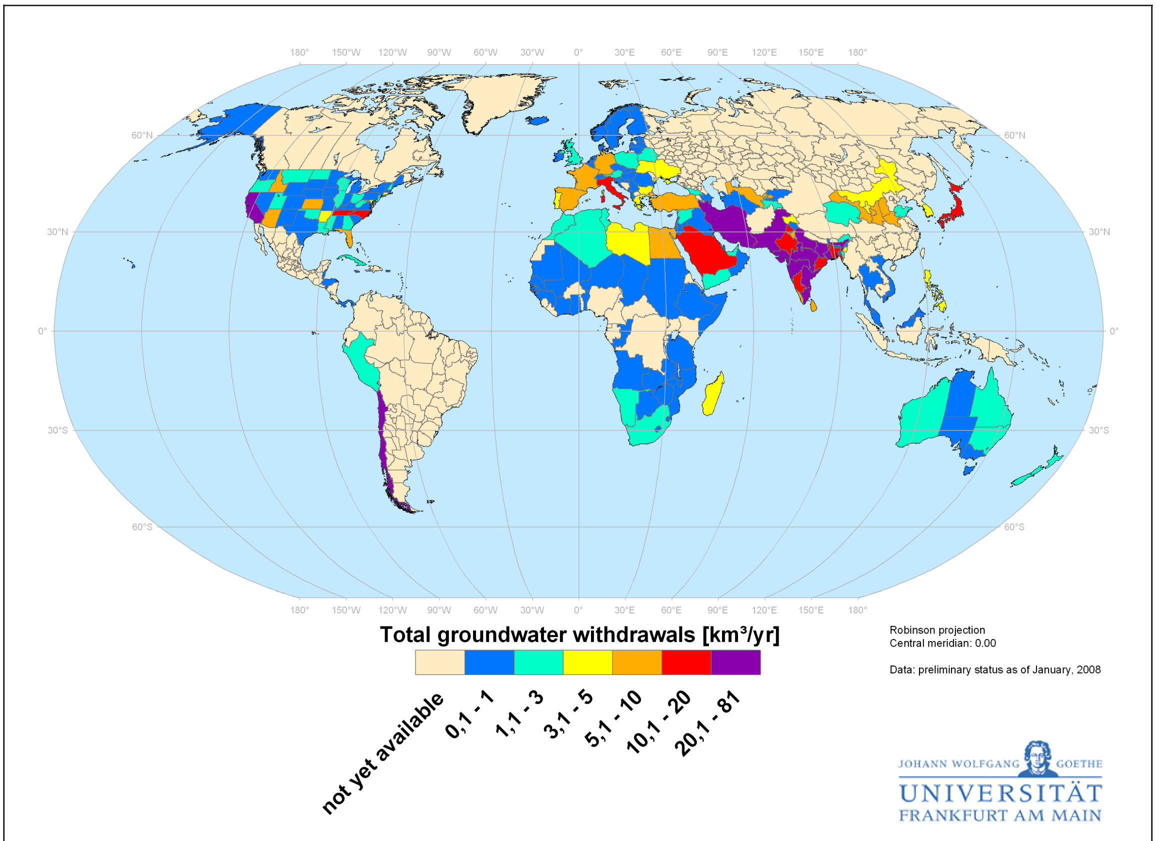


Figure 3: Total groundwater withdrawals per country/sub-national unit (km³/yr)

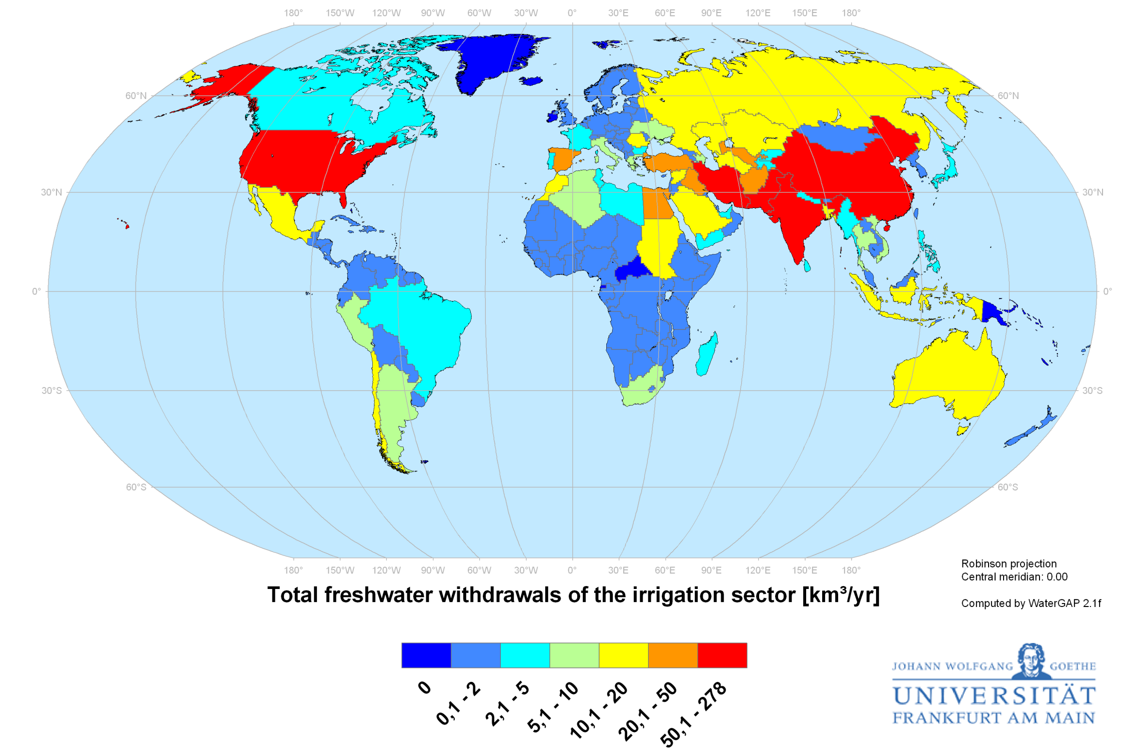


Figure 4: Total freshwater withdrawals of the irrigation sector by country, as computed by WaterGAP 2.1f, mean value for the years 1990 – 2002

Evolution of VIC-RBM

Modeling daily river discharge and water temperature modeling on macro-hydrological scale

Recent and future changes in climate will affect hydrologic and thermal regimes, having a direct impact on water quality (Ducharne, 2008; van Vliet and Zwolsman, 2008) and in turn the growth rate and distribution of freshwater organisms (e.g. Bartholow, 1991; Rundquist and Baldrige, 1990). In addition, changes in river temperature and streamflow are of economic importance for water requirements for industry, electricity and drinking water production (IPPC, 2001; Segrave, 2009).

Although integrated hydrological and deterministic water temperature modeling approaches have been successfully applied for small-scale catchments (e.g. Caissie et al., 2007; Haag and Luce, 2008; St-Hilaire et al., 2000), much less work has been done at large scales. A computationally efficient modeling approach is needed to simulate water temperature and river discharge at large temporal (>20-30 years) and spatial scales, for purposes such as addressing climate change issues. In addition, realistic simulations of daily water temperature and discharge of rivers with different basin characteristics and anthropogenic impacts are needed to address large-scale water management issues.

Within WATCH, a modeling framework for large-scale daily river discharge and water temperature modeling was developed and tested. The Variable Infiltration Capacity (VIC) model (Liang et al., 1994) and the computationally efficient 1D stream temperature river basin model (RBM) (Yearsley, 2009) which was forced with output from VIC, were used in this modeling framework. In addition, results of a global scale water temperature regression modeling study (van Vliet et al., 2011) were used to define the boundary conditions of the RBM water temperature model.

The Variable Infiltration Capacity (VIC) is a grid-based macro-scale hydrological model that solves the energy and water balance. Surface runoff and baseflow are routed along the stream network to the basin outlet using an offline routing model that used the unit hydrograph principle in the gridcells and linearized St. Venant's equations to simulate river flow through the stream channel (Lohmann et al., 1998). The routing model of VIC was modified to include the calculation of the hydraulic characteristics (with, depth, flow velocity) which are needed for the stream temperature simulations with RBM. Hydraulic characteristics were calculated based on power equations relating mean velocity, cross-sectional area and width to river discharge (Leopold and Maddock., 1953). The coefficients of these relations were obtained using the fitted empirical relations with river discharge based on 674 stations from watersheds across the United States (Allen et al., 1994). For the river reaches affected by reservoirs, water surface elevation, and consequently depth and width were assumed to remain constant in time. For details see (van Vliet et al., in prep.; Yearsley and Tang, submitted).

RBM is a deterministic (physically based) one-dimensional stream temperature model that solves the 1D-heat advection equation using the semi-Lagrangian (mixed Eulerian-Langrangian) approach (Yearsley, 2009). RBM was originally developed for small subbasins of the Columbia river, like the Salmon subbasin (36,325 km2) on a 0.0625° x 0.0625° spatial resolution (Yearsley and Tang, submitted). Water temperatures for stream segments are simulated based on the upstream water temperature and inflow into the stream segment, dominant heat exchange at the air-water surface and advected heat from tributaries and subsurface (van Vliet et al., in prep.). Within WATCH, modifications were made to apply the water temperature model for several large river basins (>~150,000 km2) characterized by different thermal and hydrological regimes on a 0.5° x 0.5° spatial resolution. Details are described in van Vliet et al. (in prep.).

The modeling approach was tested and validated for selected large river basins (Columbia, Rhine, Mekong and Lena) situated in different hydro-climatic zones and characterized by different anthropogenic impacts (van Vliet et al., in prep.). River discharge and water temperature were simulated realistically at daily time steps with a mean correlation coefficient (ρ) >0.75. Initially, larger biases in simulated river discharge and water temperature were found for the Columbia, due to large reservoirs which affect both river flow and thermal regimes. However, improvement in simulated daily river discharge and water temperatures were obtained by including a reservoir scheme and using corrected power equations relating mean velocity, cross-sectional area and width to river discharge into the stream temperature model RBM. Realistic simulations were obtained during warm, dry summers, when water temperature and river discharge are generally most critical for river functions, and also during the whole second half of the 20th century. The modeling approach has potential to perform risk analyses and studying climate change impacts on daily river discharge and water temperature at macro-hydrological scale (van Vliet et al., in prep.).

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