

Calibration of a global hydrological model against measured discharge

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Abstract The hydrological model WaterGAP 2, a global model of water availability and water use, is calibrated against time series of annual discharge measured at 724 stations, by adjusting the runoff coefficient in the respective upstream areas. The reduction of natural discharge by consumptive water use is simulated by the model in at least an approximate manner; otherwise, a comparison of modelled and measured discharges would not be possible, particularly in basins with extensive irrigation. The calibration basins cover 50% of the global land area excluding Greenland and Antarctica. For 327 stations, the calibrated runoff coefficients remain within physically plausible limits, and the model efficiency measured by the Nash-Sutcliffe coefficient is mostly satisfactory to good. The measured long-term average discharge in the other basins can only be computed if a runoff correction factor is introduced. This is due to both uncertain input data (e.g. underestimated precipitation in snow-dominated areas) and inappropriate model formulation (e.g. neglecting the loss of river water in semiarid areas).

Key words hydrological model; water use model; global model; calibration; discharge; consumptive water use; precipitation correction

INTRODUCTION

WaterGAP, a global model of water availability and water use, has been developed to assess the impact of global change on the problem of water scarcity in river basins (Döll *et al.*, 1999; Alcamo *et al.*, 2000). With a spatial resolution of 0.5°, the raster-based model is designed to simulate the characteristic macroscale behaviour of the terrestrial water cycle including human impact, and to take advantage of all pertinent information that is globally available. For each of approximately 67 000 grid cells, the hydrological model of WaterGAP 2 computes evapotranspiration and runoff by calculating daily water balances of the soil and canopy as well as of lakes, wetlands and large reservoirs (vertical water balance). The water use model simulates both withdrawal and consumptive water use of the agricultural, domestic and industrial sectors. Consumptive water use is the fraction of the withdrawn water that evaporates and does not return to the river. Discharge at each cell is determined from upstream runoff and consumptive water use by applying a global flow routing scheme.

Due to the complexity of the system, the large scale and the limited quality of the input data, the hydrological model cannot be expected to compute good discharge estimates by only using independent data sets. Therefore, it has a small number of calibration parameters. The first step of the calibration process is the calibration of the vertical water balance, which is achieved, at least approximately, by comparison with

measured annual discharge values. We calibrated the vertical water balance against time series of annual discharges measured at 724 globally distributed stations by adjusting one parameter, the runoff coefficient, in the respective upstream areas. The parameters describing the dynamics of lateral transport are calibrated in the next step. Assuming that the precipitation input is correct, the calibrated model should provide a good estimate not only of the water availability of the drainage basin but also of its evapotranspiration.

To our knowledge, this is the first calibration of a global hydrological model in a large number of drainage basins. In his study of streamflow in Europe, Arnell (1999) tuned only some model parameters uniformly across Europe, but did not perform a basin-specific calibration. As a result, a fifty percent error between simulated and observed long-term average discharge in large European river basins was not uncommon. Applying the macroscale hydrological model of Vörösmarty *et al.* (1989) at the global scale, Fekete *et al.* (1999) combined discharge measurements with model results not by calibrating the model, i.e. by adjusting some model parameters, but by introducing a correction factor that is the ratio of modelled and measured long-term average discharge. Thus, they used the hydrological model for a spatial interpolation of long-term average runoff. They did not take into account, however, that in many river basins discharge is significantly reduced by water consumption, in particular for irrigation (e.g. the Colorado River or the Yellow River), and that in those basins it is therefore impossible to derive runoff from measured discharges without considering the human use of water. Finally, land surface parameterizations of atmospheric models, which also compute runoff at the global scale, do not include basin-specific calibration parameters either, and, in general, computed discharges do not fit the measured discharges.

MODEL DESCRIPTION

For the land fraction of each cell, the hydrological model computes the canopy water balance as a function of land cover, precipitation and potential evapotranspiration (modified Priestley-Taylor approach). The resulting throughfall (together with melt water), the effective precipitation P_{eff} , is input to the soil water balance (one soil layer). Actual evapotranspiration is computed as a function of the soil water content S , maximum water storage capacity S_{max} and the potential evapotranspiration not used for evaporation of the canopy water. Total runoff R_i from the land fraction of the cell is calculated as:

$$R_i = P_{\text{eff}} \left(\frac{S}{S_{\text{max}}} \right)^\gamma \quad (1)$$

where γ is the runoff coefficient that is adjusted by calibration. S_{max} is a function of the total available water between field capacity and wilting point and the land cover specific effective rooting depth. The water balance of lakes and wetlands is modelled as the difference between precipitation and potential evapotranspiration. The total cell runoff is routed to the downstream cell (only one downstream cell possible) along a newly developed 0.5° global drainage direction map DDM30, taking into account the

storage of the groundwater, the lakes and wetlands, and the river. For the computation of annual discharge, the influence of the routing dynamics is, in most river basins, negligible.

The water use model computes the consumptive water use in each cell. On the global average, approximately 90% of consumptive water use is for irrigation. WaterGAP 2 models irrigation water use as a function of irrigated area and climate, distinguishing only rice and non-rice crops. Both discharge and irrigation water use computations rely on 1901–1995 time series of 0.5° gridded monthly climate data by New *et al.* (2000). Domestic and industrial water use of a cell is downscaled from country-level data.

CALIBRATION

The hydrological model of WaterGAP 2 was calibrated against time series of discharges at 724 measurement stations provided by the Global Runoff Data Centre (Koblenz, Germany). The minimum drainage basin size is 9000 km², and the stations along a river were selected such that the inter-station areas are generally larger than 20 000 km². The stations were co-referenced to the 0.5° drainage direction map in order to allow the comparison between measured and computed discharges. The calibration basins cover 50% of the global land area excluding Greenland and Antarctica. The calibration parameter γ is assumed to be the same for all cells located between two stations. It was adjusted such that the computed long-term average annual discharge is within 1% of the measured value over the total measurement period or, in case of long time series, over the most recent 30 measured years.

The computed discharge used for model calibration is calculated by reducing the natural discharge of each cell by the simulated consumptive water use. For each day, the consumptive use of a cell is subtracted from the cell discharge if it is high enough. Otherwise, the discharge in the neighbouring cell with the largest discharge is also reduced.

RESULTS

Figure 1 shows the location of the 724 calibration basins. In 327 basins, the runoff coefficient γ (comp. equation (1)) was calibrated to be between 0.3 and 3. These basins cover 27 million km², or 40%, of the total area of the calibration basins. If γ was calibrated to be lower than 0.3, considerable runoff occurs even if the soil is very dry, and if it is above 3, runoff is extremely small even well above the wilting point. Therefore, a γ value outside the range of 0.3–3 prevents the hydrological model from simulating the soil water dynamics in a realistic manner.

If the minimum value of γ is set to 0.3, the model underestimates discharge mainly in snow-dominated river basins (Fig. 1). This could be explained by the fact that snow precipitation is strongly underestimated by most types of precipitation gauges. To test this hypothesis, the precipitation values of New *et al.* (2000), which are based on precipitation measurements and are not corrected for measurement errors, were corrected applying the monthly precipitation correction factors by Legates & Willmott (1990). According to these data, the actual precipitation is, on the global average,

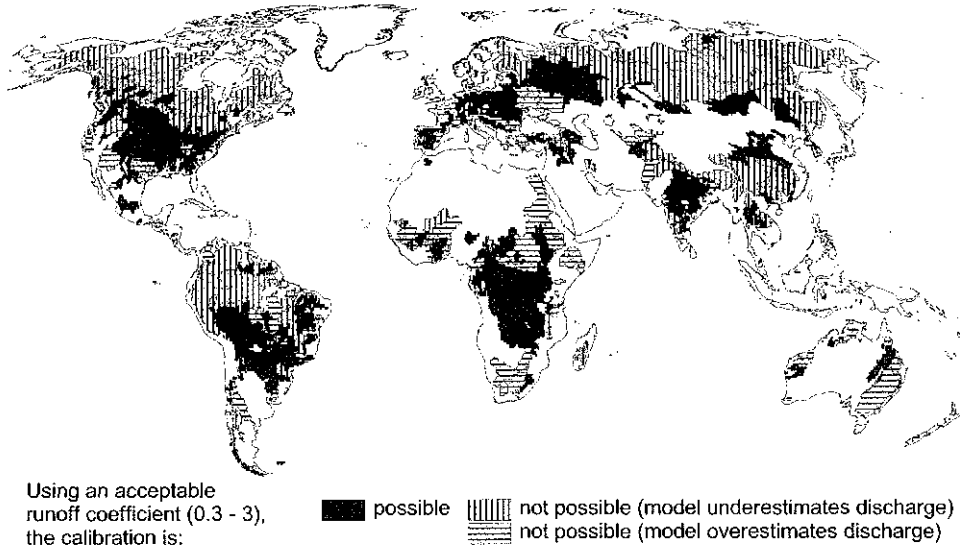


Fig. 1 River basins in which WaterGAP 2 could be calibrated by adjusting the runoff coefficient within plausible limits (0.3–3).

11% larger than measured precipitation, but up to 300% larger in snow-dominated areas. Using the corrected precipitation, the calibrated γ of many snow-dominated river basins increases significantly, i.e. it improves. However, for a very large number of other basins, the calibrated γ values then leave the plausible range and become greater than 3. For example, in some Central European basins, the Legates & Willmott (1990) precipitation correction factors appear to be too high. As no other correction factors are available at the global scale, we decided to use uncorrected precipitation.

Many of the river basins, for which the model overestimates measured discharge even if γ is set to 3, are in semiarid regions (Fig. 1). The overestimation might be due to an inappropriate model formulation. In the model, for example, losses of the river, e.g. to phreatophyte evapotranspiration, and the evaporation from many small ephemeral ponds forming after rainfall, cannot be taken into account. In river basins with large consumptive water use, a relatively small underestimation of consumptive use by the water use model of WaterGAP might lead to an overestimation of discharge that cannot be compensated by increasing γ up to the value of 3 (e.g. the lower Colorado or the Murray-Darling basins).

In general, the computed discharge is very sensitive to the uncertain precipitation input as well as to the potential evapotranspiration, which again depends on radiation data. Furthermore, in many regions of the globe, the evaporation of intercepted water or from lakes and wetlands, both of which are not adjusted by the calibration, form a large part of total evaporation, such that the adjustment of the runoff coefficient can often be ineffective for achieving a good fit between measured and computed discharges.

In the basins where the model under- or overestimates discharge with γ values between 0.3 and 3, γ was set to 0.3 or 3, respectively, and a runoff correction factor was defined as the ratio between the average of the measured discharge over the

calibration period and the average computed discharge. Whenever runoff is computed in these basins, the simulated value is multiplied by the runoff correction factor to adequately represent the measured discharge values. This procedure is similar to the approach taken by Fekete *et al.* (1999) for all river basins. In basins where such a runoff correction factor has to be applied, the model only serves to interpolate measured discharge in space and time. The dynamics of the water cycle, however, are no longer modelled correctly and, for example, the computed evapotranspiration is not consistent with the corrected runoff estimate.

The Nash-Sutcliffe coefficient C_{NS} measures the efficiency of the model by relating the goodness-of-fit of the model to the variance of the measurement data. It is defined as:

$$C_{NS} = 1 - \frac{\sum (q_c - q)^2}{\sum (q - q_{avg})^2} \quad (2)$$

where q_c and q are the computed and measured annual discharges and q_{avg} is the average measured discharge. If C_{NS} is larger than 0.5, the inter-annual variability of discharge is represented well by the computation, whereas if it is below zero, the variability is not captured at all. As expected, C_{NS} is mostly above 0.5 where the model could be calibrated (with γ between 0.3 and 3, Figs 1 and 2). Values of C_{NS} below 0.5 occur mostly where calibration was not possible, but there is also quite a number of such basins, where C_{NS} is above 0.5 (e.g. in East Asia and Europe). Possibly, a high C_{NS} value mirrors mainly the good quality of precipitation and discharge data. The hydrological model of WaterGAP 2 cannot yet simulate well the behaviour of large lakes and reservoirs with over-year storage, e.g. Lake Victoria and Lake Nasser (Aswan Dam) in the Nile basin.

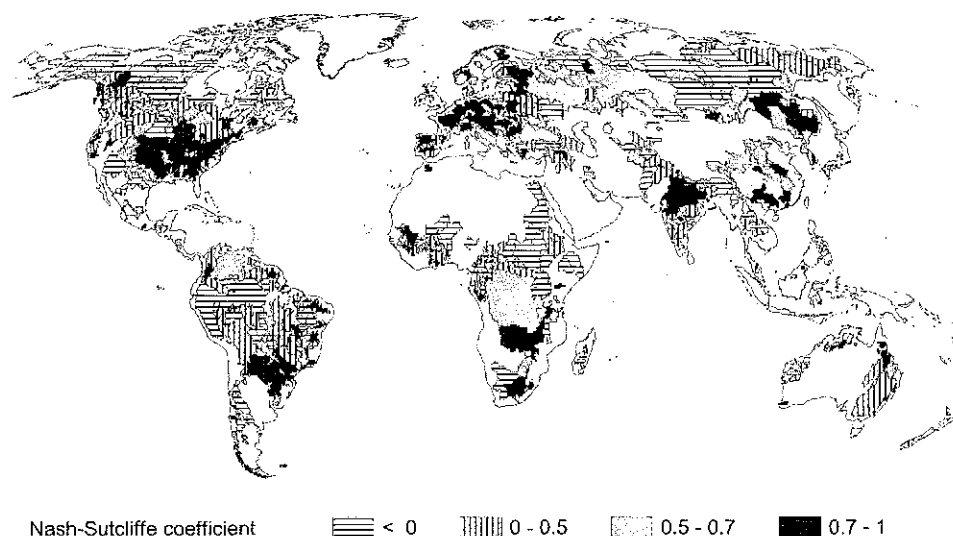


Fig. 2 Nash-Sutcliffe coefficients for annual discharges in 724 calibration basins during the calibration periods.

If computed discharge is to be compared to measured discharge, the model must take into account the decrease of natural discharge by consumptive water use. Modelling the discharge reduction is made difficult by (a) the modelling of consumptive water use itself, (b) extensive artificial irrigation canal systems across river basin boundaries, and (c) the possible use of nonrenewable groundwater or other groundwater not connected to surface water. The latter two complexities are not taken into account by our model. For the example of the Huanghe (Yellow) River at Sanmexia (China), Fig. 3 shows how much computed “actual” discharge (calculated by subtracting upstream consumptive water use) differs from the natural discharge that would occur without water use. The difference increases with time due to increased population, and industrial and agricultural activity. Further downstream of Sanmexia, discharge reduction becomes even more significant due to extensive irrigation, but there are no measurement data available for comparison.

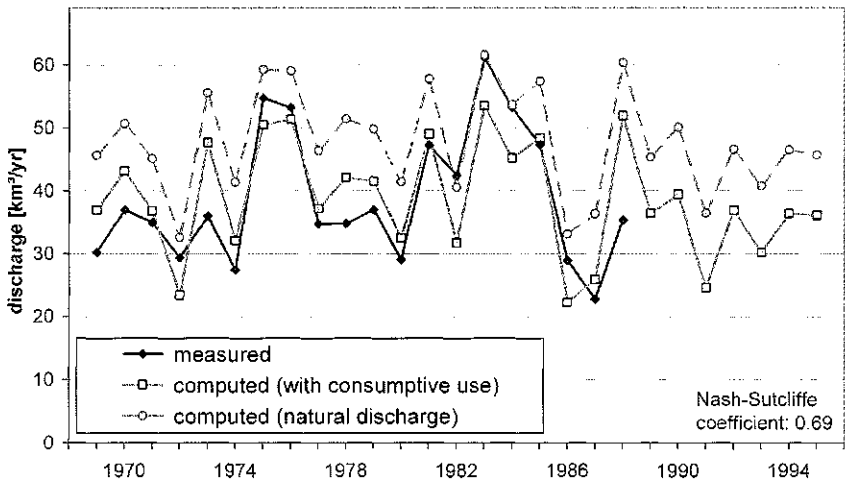


Fig. 3 Importance of taking into account water use: measured and computed annual discharge values of the Huanghe River (Yellow River) at Sanmexia. Without consumptive water, a natural discharge is simulated which is significantly higher than the actual measured discharge.

CONCLUSIONS

The partitioning of precipitation into evapotranspiration and runoff is a very complex process. Therefore, at least at large scales, it is not yet possible to model discharge by just relying on independently determined parameter sets, and a basin-specific model calibration is necessary. River discharge is the best variable against which hydrological models and land surface parameterizations of atmospheric models can be calibrated because there exist long measured time series at many locations, and discharge integrates over the drainage basin. Calibration (or validation) against discharge in river basins with significant consumptive water use (which is mainly due to irrigation) requires modelling the reduction of discharge by consumptive water use.

It was possible to successfully calibrate the hydrological model of the global water model WaterGAP 2 against annual discharge values measured at 327 stations world-

wide, i.e. the calibration parameter could be set to values within a physically plausible range. For most of these stations, the model efficiency is satisfactory to good. For the other 397 drainage basins, the calibration was not successful. This can be due to many factors, the most important being (a) the uncertain precipitation input in particular in snow-dominated regions and in regions with a low density of rain gauges, (b) inappropriate process formulation (e.g. the method to compute potential evapotranspiration), and (c) lack of knowledge about local characteristics (e.g. the characteristics of wetlands or reservoirs).

REFERENCES

- Alcamo, J., Henrichs, T. & Rösch, T. (2000) World water in 2025—global modeling and scenario analysis for the World Commission on Water for the 21st Century. *Report A0002. Center for Environmental Systems Research, University of Kassel, Kassel, Germany.*
- Arnell, N. W. (1999) A simple water balance model for the simulation of streamflow over a large geographic domain. *J. Hydrol.* **217**, 314–335.
- Döll, P., Kaspar, F. & Alcamo, J. (1999) Computation of global water availability and water use at the scale of large drainage basins. *Mathematische Geologie* **4**, 111–118.
- Fekete, B. M., Vörösmarty, C. J. & Grabs, W. (1999) Global composite runoff fields of observed river discharge and simulated water balances. *Report no. 22. Global Runoff Data Centre, Koblenz, Germany.*
- Legates, D. R. & Willmott, C. J. (1990) Mean seasonal and spatial variability in gauge-corrected, global precipitation. *Int. J. Climatol.* **10**, 111–117.
- New, M., Hulme, M. & Jones, P. D. (2000) Representing twentieth century space-time climate variability. Part II: Development of 1901–96 monthly grids of terrestrial surface climate. *J. Climate* **13**, 2217–2238.
- Vörösmarty, C. J., Moore, B., Grace, A. L., Gildea, M. P., Melillo, J. M., Peterson, B. J., Rastetter, E. B. & Steudler, P. A. (1989) Continental scale models of water balance and fluvial transport—an application to South America. *Global Biogeochemical Cycles* **3**, 241–265.