Global water-balance modelling with WASMOD-M: Parameter estimation and regionalisation

Elin Widén-Nilsson a,*, Sven Halldin a, Chong-yu Xu a,b

a Department of Earth Sciences, Air, Water and Landscape Sciences, Uppsala University, Villavägen 16, SE-752 36 Uppsala, Sweden
b Department of Geosciences, University of Oslo, P.O. Box 1047, Blindern, NO-0316 Oslo, Norway

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Summary Limitations in water quantity and quality are among the greatest social and economic problems facing mankind. However, difficulties in estimating the global long-term average runoff have led to differences of as much as 30% when integrated to the whole earth. Model estimates of runoff are especially uncertain for the 50% of the global land surface lacking consistent runoff data. In this study, we present the WASMOD-M global water-balance model, constructed to provide robust runoff estimates both for gauged and ungauged basins. WASMOD-M is a conceptual water-budgeting model with two state-variables and five tunable parameters. A simple parameter-value estimation procedure allowed "acceptable" parameter values to be identified both for the majority of gauged basins, and for most ungauged basins. Acceptable global simulations could be accomplished with continentally constant parameter values but at the cost of compensating errors on a basin scale. A "standard", spatially-distributed parameter-value set was derived for a "best" global simulation. Of the simulated 59132 0.5° × 0.5° cells, 45% got "good" parameter values as a by-product of regionalisation, 41% from regionalisation, whereas 14% were given a default value set. This global set allowed simulation of the 1915–2000 world water balance. The simulation was in the same range as previously published model results and compilations of runoff measurements. Long-term average within-year runoff variations agreed well with previously published results for most of the studied runoff stations although WASMOD-M was only calibrated against long-term average runoff. Improvement of WASMOD-M and other global water-balance models should be simplified by a common definition of basin boundaries and areas, as well as runoff. Further, modelling progress will depend on improved global datasets of precipitation and runoff regulation.

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* Corresponding author.
E-mail addresses: elin.widen@hyd.uu.se (E. Widén-Nilsson), sven.halldin@hyd.uu.se (S. Halldin), chongyu.xu@geo.uio.no (C.-y. Xu).
Introduction

The world population is learning to cope with limited water resources. In spite of its central importance to mankind, the difference between estimates of global runoff is around 30% and up to 70% for individual continents (GRDC, 2004). Access to high-quality water-balance data from local to global-scales is one of the most important prerequisites for the planning of sustainable development. Such data are, however, completely lacking in many developing countries (GRDC, 2005). This makes water-balance measurement compilations and model estimates unreliable for those regions and focuses attention on methods to extrapolate to regions where information is lacking (IAHS, 2003).

Global-scale problems have motivated, in the last 10–15 years, development of global water-balance models. Problems that require global-scale water data include climate-change impact, virtual water trade, water conflicts in multinational river basins and rapidly increasing water demand from a growing world population (Döll et al., 2003; Arnell, 2003; Oki and Kanae, 2006). Global water-balance models may also provide a basis to establish long-term data-collection programmes in places where these are missing.

In climate-change studies, global water-balance models can be important tools in developing consistent hydrological properties and variability over large spatial domains (Arnell, 1999b, 2004; Vörösmarty et al., 2000a; Alcamo andHenrichs, 2002). Understanding of land-surface processes and their parameterisation in general circulation models (GCMs) has improved but large uncertainties still remain (Kabat et al., 2004), particularly concerning runoff. Many GCMs treat runoff as a residual discarded from the land surface to the ocean after each time step. Water flows are primarily considered at the interfaces between the atmosphere and the ocean on one hand and the land surface on the other. GCMs are still the only way to provide consistent long-term input data to global water-balance models but the quality of GCM precipitation remains insufficient with respect to amount as well as to occurrence (Mearns et al., 1995; Bates et al., 1998; Xu, 1999a; Arora, 2001).

Present-day global water-balance models work with a spatial resolution of 0.5°×0.5° latitude–longitude and monthly input data (Fekete et al., 1999a; Arnell, 2003; Döll et al., 2003). Validation data are restricted by the large degree of regulation of the many major water courses which, without information on operational rules, cannot be simulated. Since, global data, especially time series, have incomplete information on regulation of large rivers (Vörösmarty et al., 1997; Nilsson et al., 2005), it is difficult to know whether runoff variability refers to regulated or to natural conditions. Additionally, anthropogenic influences, such as water abstractions, can considerably alter the runoff in the downstream parts of a basin (Döll et al., 2003). Hence, validation must primarily be done on long-term average runoff data. The robustness of water-balance models can suffer from problems of overparameterisation and equifinality (Franks et al., 1997) with such limitations in input and validation data.

Since, neither global-change predictions nor runoff in ungauged basins can be studied in vitro, one way to increase the goodness of water-balance predictions and extrapolations is to subject models to internal tests that reveal their capacity to predict spatial and temporal variations of changes in water-balance components. In this paper we present the new WASMOD-M (M for macro-scale) global water-balance model based on the WASMOD (Water And Snow balance MODeling system) catchment model (Xu, 2002). We selected WASMOD as our starting point because its simple structure and few parameters were in line with the global-modelling data limitations. As summarised in Xu (2002), different versions of WASMOD have shown a high level of generality from applications at variously-sized catchments in Europe, Asia and Africa. Studies have shown that its model parameters can be correlated with catchment characteristics (Xu, 1999b, 2003; Muller-Wohlfeil et al., 2003) such as land-cover fractions and soil texture. WASMOD (Xu, 1999c), together with the models of Refsgaard and Knudsen (1996) and Donnelly-Makoweckia and Moore (1999), are also the only water-balance models that we have been able to locate that passed the full split-sample-proxy-basin test proposed by Klemes (1986).

The first objective of this study was to complement existing global water-balance models with a new one (one way to improve uncertainty estimates of global and continental runoff is by comparing independent models and compilation methods). Furthermore, a methodology for regionalisation of parameter values of the ungauged basins of the world, which amount to 50% of the global land surface in the Global Runoff Data Centre (GRDC, 2005), should be outlined. A third objective was to find out if one, or a very small number of parameter-value sets, could be used to produce acceptable global and continental water balances, i.e. to find out how simple a model could be designed that reasonably reflects the global water balance.

Global models and data requirements

Simulation of the global water balance can be done with different types of models. The global water-balance models are simple models, transferring precipitation to evaporation and runoff. The three main global water-balance models are WBM (Vörösmarty et al., 1989, 1996, 1998), Macro-PDM (Arnell, 1999a, 2003) and WGHM (Döll et al., 2003; Kaspar, 2004), a submodel of WaterGAP (Döll et al., 1999; Alcamo et al., 2003). WASMOD-M, as presented here, is a new model in this category. Runoff is also produced by globally operating dynamic vegetation models like LPJ (Gerten et al., 2004), and Soil-Vegetation-Atmosphere-Transfer (SVAT) models like VIC, used as a land-surface scheme in some atmospheric GCMs (Liang et al., 1994; Nijssen et al., 2001a). Routing models like HD (Hagemann and Dümenil, 1998) simulate global runoff when combined with atmospheric GCMs.

 Principally, parameter-value tuning is necessary for all models because of limited data quality, complexity of processes, and subgrid spatial heterogeneity (Döll et al., 2003) even though it would ideally be avoided (Arnell, 1999a). Nijssen et al. (2001a) report on the improvements in model performance found when land-surface-parameterisation schemes and macroscale hydrological models were calibrated against runoff. This was true for conceptual as well as for physically-based models.
The three main global water-balance models have different approaches to calibration or tuning. WBM has parameter values assigned \textit{a priori} (Vörösmarty et al., 1998) and it is not calibrated. The parameter values are related to vegetation and soil properties, or assumed constant. Vörösmarty et al. (1998) use WBM to compare different estimates of potential evaporation. Fekete et al. (1999a) apply runoff-correction factors in gauged cells to make inflow to downstream areas equal to measured flow. For calibration of WTM, the water-transport model in WBM, the reader is referred to Vörösmarty et al. (1989), Vörösmarty and Moore (1991), and Vörösmarty et al. (1996).

Arnell’s (1999a, 2003) approach is to avoid calibration as much as possible. Macro-PDM parameter values are estimated from spatial databases or assumed constant from the literature values and using knowledge of previous applications of the model (Arnell, 2003). Six of the 13 parameters are globally uniform and 7 are functions of soil texture and vegetation (Arnell, 2003). When developing the model, Arnell (1999a) did some tuning to set values and test model sensitivity. The tuning process includes tests of precipitation datasets and potential evaporation calculations and is done against long-term average runoff and long-term average within-year runoff patterns.

The approach of Döll et al. (2003) is to calibrate only one WGHM parameter, which regulates runoff based on effective precipitation and available soil water. Calibration is carried out against measured long-term average runoff to get a simulated maximum error of 1%. This goal is achieved for all 724 stations after applying one or two correction factors in 339 cases to ensure that the downstream stations get simulated runoff similar to the measured. Döll et al. (2003) regionalise their calibrated parameter with multiple regression against long-term average temperature, freshwater area, and length of non-perennial river stretches. A subset of the calibration basins is included in the regression but correction factors are not regionalised. The other WGHM parameter values are globally uniform or related to land cover and its associated properties (e.g. albedo and rooting depth), leaf mass, slopes, soil/bedrock properties and climate variables (e.g. temperature).

Availability and preparation of input data files is a major problem in global water-balance modelling. Uncertainties and differences in model-input data, especially precipitation, are major sources of uncertainty in model output. Arnell (1999a) states that, with a rudimentary sensitivity analysis of Macro-PDM for Europe, macro-scale models are primarily constrained by the quality of the input data, while “estimated model parameters and model form are less significant”. Döll et al. (2003) list erroneous input data (primarily precipitation but also radiation) as the first reason for the need of calibrating WGHM. Kaspar (2004) proves, through careful sensitivity analysis of WGHM, that other factors are more important for the model uncertainty than the precipitation errors, although the results would improve with precipitation corrected for gauge undercatch. Fekete et al. (2004) use WBM to study the impact of different precipitation datasets on runoff estimation. Vörösmarty et al. (1998) test different potential evaporation functions for the same purpose. These two WBM studies show the need for accurate precipitation inputs for water balance calculations and that arid and semiarid regions are very sensitive to precipitation input while the sensitivity for potential evaporation functions is more pronounced in humid areas.

Materials and methods

Data preparation

The global water-balance model WASMOD-M was driven by the freely available CRU TS 2.02 climate data (Mitchell et al., 2004). Basin boundaries and areas, flow paths, and continent boundaries were taken from STN-30p (Vörösmarty et al., 2000b). These datasets have grid cells with identical projection and 0.5° × 0.5° latitude—longitude resolution but differing land-sea masks. The CRU climate dataset includes land-surface cells with smaller land-surface fractions than the STN-30p physiographic dataset. We used, conservatively, the land mask implicitly defined by STN-30p (59132 cells). Seven cells in this were not covered by CRU and climate values of these were set to an average of the eight surrounding cells. CRU climate data cover the period 1901–2000 whereas long-term runoff averages from GRDC (2004, 2005) are based on different time periods during the 20th century. Some gauging stations include data from the 19th century.

Climate-input data to WASMOD-M comprised gridded monthly values of precipitation, temperature and water-vapour pressure. Precipitation-correction factors were calculated for gauge losses as quotients for each cell between corrected and uncorrected precipitation (Willmott et al., 1998; Legates and Willmott, 1990) as a long-term average for each month. We only used correction factors between 1 and 3.4. The correction increased total global precipitation by 9%. Measured runoff from 663 gauging stations in 257 basins discharging to oceans or large lakes was used for parameter-estimation and model validation. The runoff data were included in “UNH/GRDC Composite Runoff Fields V1.0” (Fekete et al., 1999b, 2002), where station positions are slightly relocated to fit into their 0.5° flow paths. The STN-30p dataset delineates 6132 basins, of which 4226 are small covering one or two cells only. 257 of these 6132 basins correspond to 50% of the global surface area and have runoff data from gauging stations that have been running for variable time periods, none of which were reported beyond 1997. Related to the actively discharging area only, the coverage is 72% instead of 50% (Fekete et al., 2002).

Almost all large rivers are regulated (Vörösmarty et al., 2004; Nilsson et al., 2005) such that natural peak- and low-flow characteristics are modified. Regulation data are often unavailable since dam and reservoir operation commonly involve competing economic interests and can also be in conflict with downstream water-supply needs (Brakenridge et al., 2005). Many hydrological models, therefore, do not include regulation effects. Flow data from regulated rivers are sometimes naturalised, i.e. recalculated to their natural behaviour by subtracting anthropogenic effects like abstraction and damming, to overcome this problem, but no global database of naturalised streamflow exists. We used long-term-average runoff in this study instead of time series to minimise the effect of the regulation problem on model calibration. We assumed that regulation did not affect average flow volumes, a non-valid assumption in warm and arid
areas with substantial evaporation loss from river stretches and reservoirs, e.g., in the Nile. We did also not correct for water extraction, a problem, e.g., in the Yellow River and Colorado River basins.

The combination of precipitation and runoff data showed that some basins had physically unreasonable runoff coefficients. We estimated parameter values only from basins with runoff coefficients between 1% and 85%. Regions where these problems were abundant were excluded altogether, e.g., Alaska and the Colorado River basin.

**Model description**

WASMOD-M updates the storage of water in each cell by adding precipitation and subtracting calculated evaporation and runoff. Gridded datasets of precipitation, temperature, and potential evaporation are used as input to calculate the runoff from each cell. WASMOD-M calculates snow accumulation and melt, actual evaporation, and separates runoff into a fast and a slow component with a monthly time step. The model allows snow, rain, and also melting to simultaneously occur in the same month. The model has 4–6 parameters (model constants; Table 1), depending on the presence of snow or not, of which 5 have been varied in the parameter-estimation procedure. All units are mm month\(^{-1}\) unless stated otherwise.

### Potential evaporation

Potential evaporation (ep) is pre-processed and used as input. Xu (2002) reviews different potential evaporation equations depending on data availability. In this case it was calculated from air temperature, \(T_a(\degree C)\), and relative humidity, RH (%) calculated from temperature and water-vapour pressure:

\[
ep = E_c \times (T_a - T_m)^2 \times (100 - \text{RH})
\]  

(1)

where \(T_m = \max(T_a, 0)\). The parameter \(E_c\) was set to 0.018 (mm month\(^{-1}\) °C\(^{-2}\)) globally.

\[
\begin{align*}
evap = \min(\{(\text{ep-dl}) \times (1 - \frac{\text{available water}}{\text{ep-dl}})), \text{available water}\} & \quad \text{ep-dl} > 1 \\
evap = \text{ep-dl} & \quad \text{ep-dl} \leq 1
\end{align*}
\]

**Snow accumulation and melt**

Snow and rainfall as well as snowmelt and accumulation vary exponentially between two temperature thresholds (\(T_m\) and \(T_s\)). The snow equations were applied only for grid cells where at least one monthly average temperature fell below 4 °C:

\[
\text{snow} = P \times \left\{1 - \exp\left(-\left(\frac{T_s - T_m}{T_s - T_m}\right)^2\right)\right\}^{+}
\]

(2)

\[
\text{rain} = P - \text{snow}
\]

(3)

\[
\text{melt} = (\text{snowpack}_{\text{old}}/\Delta t + \text{snow})
\]

(4)

\[
\text{snowpack} = \text{snowpack}_{\text{old}} + (\text{snow-melt}) \times \Delta t
\]

(5)

where \(P\) is precipitation and \(\Delta t = 1\) month. \(\{x\}^{+}\) means \(\max(x,0)\), and \(\{x\}^{-}\) means \(\min(x,0)\).

**Evaporation**

Direct water loss (dl) to the atmosphere is calculated from potential evaporation and rainfall. The variable "land moisture" (in mm) represents the storage of water available for evaporation and runoff in the next time step. The name is introduced to make a clear distinction to the well-defined, local-scale, soil-physical entity "soil moisture". Available water is calculated from active rain, i.e., rainfall minus direct loss, and snowmelt. Actual evaporation (evapot) is calculated from land moisture, potential evaporation (ep), and direct loss:

\[
\begin{align*}
\text{dl} &= \text{ep} \times (1 - e^{-\text{ep}/\text{ep}}) & \text{ep} > 1 \\
\text{dl} &= \text{ep} & \text{ep} \leq 1
\end{align*}
\]

(6)

\[
\text{active rain} = (\text{rain} - \text{dl})^{+}
\]

(7)

\[
\text{available water} = \frac{\text{land moisture}_{\text{old}}}{\text{dt}} + \text{active rain} + \text{melt}
\]

(8)

### Table 1: The complete set of parameters in the WASMOD-M global water-balance model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Governing</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_d(\degree C))</td>
<td>Snowfall (Eqs. (2) and (4))</td>
<td>1.5, 3.5</td>
</tr>
<tr>
<td>(T_m(\degree C))</td>
<td>Snowmelt (Eqs. (2) and (4))</td>
<td>−1.5, −3.5</td>
</tr>
<tr>
<td>(A_e(\text{month}^{-1}))</td>
<td>Actual evaporation (Eq. (9))</td>
<td>0.35, 0.55, 0.75</td>
</tr>
<tr>
<td>(P_\text{f}(\text{mm}^{-1}))</td>
<td>Fast runoff (storm flow, Eq. (12))</td>
<td>0.000005, 0.000001, 0.00001, 0.00014, 0.0004, 0.001, 0.0025, 0.005, 0.014, 0.019, 0.025, 0.04, 0.06, 0.08, 0.09</td>
</tr>
<tr>
<td>(P_\text{r}(\text{mm}^{-1}))</td>
<td>Slow runoff (baseflow, Eq. (11))</td>
<td>0.0000005, 0.0000001, 0.000001, 0.000005, 0.00001, 0.000025, 0.00005, 0.0001, 0.0005, 0.00095, 0.001, 0.0025</td>
</tr>
</tbody>
</table>

The combination of all values generate 1,680 globally-fixed parameter-value sets. One additional parameter, \(E_c\) (Eq. (1)), governs the pre-processing of temperature and humidity data into potential evaporation. This parameter was set to 0.018 (mm month\(^{-1}\) °C\(^{-2}\)).
evaptot = \{\text{evap} + \text{dl}\}^{-1} \tag{10}

where $A_e$ is a tuneable parameter.

**Slow and fast runoff, and water balance**

The slow runoff is a base flow, provided by land moisture whereas the fast runoff is provided by both land moisture and water added (i.e. melt + active rain) during a time step. Both runoffs are described by linear reservoirs:

\[
\text{slow} = P_s - \text{land moisture}_{\text{old}} 
\tag{11}
\]

\[
\text{fast} = P_f - \text{land moisture}_{\text{old}} + (\text{melt} + \text{active rain}) \tag{12}
\]

where $P_s$ (month$^{-1}$) and $P_f$ (mm month$^{-1}$) are tuneable parameters.

The grid cell runoff, which is the sum of slow and fast runoff, is routed downstream without delay along the flow network, i.e. flow is summed along the flow paths for each time step. There is no interaction between upstream and downstream runoff generation, i.e. all cells are independent:

\[
\text{runoff} = \text{slow} + \text{fast} \tag{13}
\]

The water balance is finally achieved by updating land moisture in each cell:

\[
\text{land moisture} = \text{land moisture}_{\text{old}} + (\text{active rain} + \text{melt-evap-runoff}) \times \Delta t \tag{14}
\]

**Parameter-value estimation in gauged basins**

Simulation results with different parameter values were compared against observed long-term average runoff, to find acceptable parameter values. Parameter values that produced unreasonable state-variable (snowpack and land moisture) values were discarded. The primary goal of the estimation was not to produce the best possible runoff in all gauged basins but to produce sets of acceptable parameter values in each cell that could be used to regionalise, i.e. to estimate parameter values in neighbouring ungauged-basin cells.

WASMOD-M was first run with a combination of globally-uniform parameter-value sets, covering the range of “reasonable” values for each parameter (Table 1). These were deduced from previous studies using the WASMOD catchment model (Vandewiele et al., 1992; Xu et al., 1996; Xu, 2002). The most sensitive parameters were given the broadest range of possible values (Table 1). The combination of the discrete values for all the parameters resulted in 1680 simulations. All the sets of values that produced acceptable runoff for a gauged basin were selected at first. Then, when the regionalisation procedure was completed, the best parameter-value set for each gauged basin was selected for the final simulation.

Parameter-value sets were considered “acceptable”, if the simulated basin runoff differed by less than ±20%, or 5 mm in dry areas, respectively, from the measured value, given that land moisture, snowpack, and change in snowpack had to be reasonable during the simulation period. Land moisture was not allowed to exceed 1000 mm in any month while the snowpack limit was 1200 mm. The average land moisture and snowpack, respectively during the first simulation year (1915) was not allowed to differ more than 200 mm and 100 mm, respectively compared to the average of the last simulation year (2000). These limits were based on previous model experience (Vandewiele et al., 1992; Xu et al., 1996; Xu, 2002).

In basins with more than one gauging station, an interstation algorithm allowed cells to be tuned to the runoff generated between stations if the runoff coefficient was acceptable. Interstation runoff was not considered if the sum of headwater and simulated interstation runoff produced unacceptable results, i.e. volume error larger than ±20%. The interstation algorithm was also overruled if it increased the error at the downmost gauging station compared to a calibration for the whole basin against runoff at this station.

**Regionalisation**

Regionalised parameter-value sets were assigned to grid cells belonging to ungauged basins and to gauged basins where no acceptable sets were found in the calibration runs. Regionalisation is probably best for surrounding areas close to gauged areas. Thus, regionalisation was conducted by searching for a common parameter-value set among all acceptable sets in surrounding gauged areas. Surrounding cells were found in a window (Fig. 1), which was moved over cells without or with non-acceptable parameter-value sets. A rectangular window form was used because climate varies more with latitude than with longitude. The most commonly occurring parameter-value set among the gauged basins in this window was selected for each given cell. If two or more parameter-value sets were equally common, the combination that gave the lowest error in the neighbouring cells was selected. Cells where no gauged basin or common parameter-value set was found within the moving window were given a single, default value set. Cells belonging to stations where the 20%-error limit was not reached were not regionalised but given the best available parameter-value set with an error above 20%.

The default parameter-value set was subjectively derived from a map (not shown) of acceptable parameter values for all gauged and regionalised cells. The map showed a few dominating parameter-value sets close to the areas with missing values. The most abundant of these was chosen as default.

**Simulations**

All simulations started with globally uniform initial values of land moisture and snowpack. A 14-year warming-up period, 1901–1914, was used to obtain physically reasonable state-variable values. The time step used was 1 month and simulations were evaluated for the time period 1915–2000.

Simulations were first performed for regionalisation. This required a simulation for each of the 1680 parameter-value sets. Only data from gauged areas were saved for further analysis.

Estimation of global and continental water balances was carried out in four steps. Continental runoff was cumulated using the continental boundaries in STN-30p and one geographically-distributed global parameter-value set, which was called the "standard simulation" set, was compiled to
In this first step we selected parameter-value sets from the 1680 globally uniform sets to give the best fit to long-term average runoff in all gauged basins, and from the regionalisation procedure for the remaining basins.

In a second step, an uncertainty analysis of this "standard simulation" was performed. This was done using the original simulations with all 1680 parameter-value sets. Sets that produced simulations within ±20% of the sum of all measured runoff were analysed to see if a single globally-uniform parameter-value set could be used to acceptably simulate not only global but also continental runoff. Total global and continental runoff with the "standard simulation" was compared with previously published estimates.

Although, the model was not explicitly tuned to within-year runoff patterns, its capability to capture these with the "standard" simulation was compared to published simulations in a third step. A set of 15 gauging stations was selected that could be compared with results in at least two previous publications using other models.

The final step in producing a good runoff estimate was to allow state-variable values to exceed their limits, if necessary many fold, if acceptable runoff could not be achieved otherwise.

Results

Regionalisation

The simulations with 1680 globally uniform parameter-value sets produced acceptable results for the whole upstream area that comprises the mainstream sub-basins of 485 of the 663 stations (Fig. 1). The 178 non-accepted stations were divided into the following four categories: In the first category, 57 stations lacked input and validation data that produced acceptable runoff coefficients. The other three categories were the result of either data or model deficiencies: No acceptable parameter-value sets could be found for 29 stations, i.e. they exceeded the 20%-error limit criterion; 23 stations had unreasonable state variables for all parameter-value sets (e.g. the snowpack or the land moisture grew too large); 69 stations had no acceptable parameter-value set with acceptable state-variables.

After applying the interstation algorithm ("Parameter-value estimation in gauged basins" Section), parameter values could be set for 531 of the total 663 stations. Since, some of them were substituted by parameter values from downstream stations, the number of parameter-value sets was finally 429. These correspond to 42% of all cells. The regionalisation procedure allowed another 41% of all cells to get parameter values. A total of 14% of all cells could not be addressed by the regionalisation procedure. The remaining 3% of all cells belonged to stations that did not reach the ±20% error limit, but had an acceptable runoff coefficient and at least one parameter-value set with acceptable state-variables. These stations were given the parameter-value set that gave the lowest error, but above 20%.

Regionalisation was fully successful in 46% of the cells, i.e. there existed a common parameter-value set for all station cells in the window. Regionalisation was partly successful in 42% of the cells, i.e. a common parameter-value set could be identified in the majority of station cells in the window. Regionalisation was less successful for 12% since parameter-value sets could only be found for less than half of the station cells in the window when only parameter values common for at least two basins were accepted.

The regionalisation failed for 14% of the land-surface cells (Fig. 1) for two reasons. Areas bordering the Arctic, Central America, the southern part of South America, parts of Northern Africa and Saudi Arabia, Indonesia and New Zealand were too far away from station cells with the given size of the moving window. No common parameter-value set could be found in parts of Turkey, eastwards towards central Asia, in south-central Australia and some small areas in Asia, Africa and America.

Global and continental water balances

Globally, 717 of the total 1680 parameter-value sets produced runoff within ±20% of the measured values integrated.
over all gauged areas (Fig. 2). With a ±1%-error limit, 54 sets remained. Simulations with these 717 parameter-value sets integrated the different continents to a globally acceptable runoff. However, none of these globally-uniform sets could produce acceptable simulations of runoff from all continents. The best globally-uniform parameter-value set, based on results for each continent, produced continental runoff errors up to 48%. All acceptable globally-uniform parameter-value sets produced overestimated runoff from Europe. All sets caused state-variable problems at some point, and some basins even showed problems with all parameter-value sets, e.g. stations in the Amazon, Cauvery, Columbia, and Danube basins.

Runoff was well simulated with WASMOD-M for all continents (Table 2, Fig. 3) with the geographically distributed parameter-value set, which produced runoff within ±20% of the measured for 455 of the total 663 gauging stations. Simulation results within ±1% were achieved for 276 stations.

Continental and global runoff values were in the same range as measurement compilations and comparable investigations (Table 2). Runoff was simulated 3–23% better for individual continents with continentally-uniform parameter values, than with the globally distributed parameter-value set, but at the cost of compensating errors at the basin scale.

Within-year runoff variations

The long-term average within-year variations were reasonably well captured for most of the 663 stations. There was a general tendency that simulated runoff varied more than the measured (e.g. Mackenzie in Fig. 4), while there were a few examples of the opposite (e.g. Yenisey in Fig. 4). There was also a tendency for around 40% of the gauging stations that the simulated peak flows occurred earlier than the measured (e.g. Mackenzie, Mississippi and Guadalquivir in Fig. 4), while a delayed peak only occurred at 15% of the stations.

Discussion

Model performance, parameter-value estimation and regionalisation

One objective in this study was to see how simple a model could be to yield acceptable continental and global runoff simulations, given available input and validation data. It was not expected that a globally-uniform parameter-value set would be able to produce acceptable continental runoff. In this study, one set of geographically-distributed parameter values, estimated with a simple procedure, was able to simulate a global runoff, that agreed well with measurement compilations and comparable simulation studies, as well as with runoff at the calibration stations. In spite of its simplicity, it may be questioned if WASMOD-M also is overparameterised as long as only long-term average runoff is used for validation. Tuning the model against within-year runoff variations (like Arnell, 1999a), evaporation patterns (Vörösmarty et al., 1998), or climatic water balance (Dai and Trenberth, 2002) would probably allow identification of more parameter values, but these additional calibration data are still uncertain.

Snowpack and land moisture problems could depend on the model, input data, or validation data. We experienced state-variable problems for 23 stations in seven basins on four continents in the simulations with globally-uniform parameters: North America, South America, Europe and Asia. Nine additional stations in four basins that were excluded because of unreasonable runoff coefficients received regionalised parameter values that produced state-variable problems. The problems we experienced with land moisture in the Amazon basin can be compared to the correction factors Döll et al. (2003) introduced in the same basin to achieve an acceptable calibration.

Problematic model-parameter values in sub-basins of larger river systems are not much discussed in the literature, but implicitly shown by Döll et al. (2003), who introduce a multiplicative correction factor, limited to 100%, for upstream gauging stations to assure that all downstream stations get simulated runoff similar to the measured. Also Fekete et al. (1999a) introduce such a factor, ranging between 0.01 and 100 (and beyond), when necessary.

The globally distributed parameter values used by WASMOD-M in its "standard simulation" were a by-product of the regionalisation procedure. This procedure was able to set parameter values for the majority of the ungauged basins in the world. The global runoff pattern produced by the "standard" parameter-value set, where around 50% of the cells were regionalised or given a default parameter value, showed a reasonable pattern (Fig. 3). A cell-by-cell comparison to other model results would probably show big differences since WASMOD-M used constant parameter values within basins in contrast to the WBM, Macro-PDM and WGHM models, where parameter values are varied according to non-runoff factors such as vegetation and soil type.

Since, around 45% of the regionalised cells had common parameter values for all stations within the regionalisation window, these would not be very sensitive to a missing station. The 10% regionalised cells that got values...
from a minority of the surrounding stations might have been sensitive to the selection of proxy stations. The size of the regionalisation window was the result of a subjective balance between the need to cover large areas while at the same time avoiding regions with too different properties.

Table 2 Global and continental runoff estimates in km$^3$/year (many data may not be directly comparable because of different continental boundaries and averaging periods)

<table>
<thead>
<tr>
<th>Continent</th>
<th>Area$^a$ (10$^6$ km$^2$)</th>
<th>Data-based estimates</th>
<th>Combined estimates</th>
<th>Model estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>K78</td>
<td>L79</td>
<td>BR75</td>
</tr>
<tr>
<td>Europe</td>
<td>10.1</td>
<td>2970</td>
<td>3110</td>
<td>2564</td>
</tr>
<tr>
<td>Asia</td>
<td>44.0</td>
<td>14,100</td>
<td>13,190</td>
<td>12,467</td>
</tr>
<tr>
<td>Africa</td>
<td>30.1</td>
<td>4600</td>
<td>4225</td>
<td>3409</td>
</tr>
<tr>
<td>North America</td>
<td>22.4</td>
<td>8180</td>
<td>5960</td>
<td>5840</td>
</tr>
<tr>
<td>South America</td>
<td>17.9</td>
<td>12,200</td>
<td>10,380</td>
<td>11,039</td>
</tr>
<tr>
<td>Oceania</td>
<td>8.66</td>
<td>2510</td>
<td>1965</td>
<td>2394</td>
</tr>
<tr>
<td>Global (except Antarctica)</td>
<td>133</td>
<td>44,560</td>
<td>38,830</td>
<td>37,713</td>
</tr>
</tbody>
</table>

| K78     | Korzun et al. (1978), Table 157, time period not specified. |
| L79     | L’vovich (1979), Table 20, time period not specified. |
| BR75    | Baumgartner and Reichel (1975), Table XXXV, time period not specified. |
| S97     | Shiklomanov (1997), Table 4.2, time period 1921–1985. |
| F02     | Fekete et al. (2002), Table 3, model WBM and data, almost equal to Fekete et al. (1999b), time period not specified. |
| F99bm   | Fekete et al. (1999b), model WBM, time period not specified. |
| O01     | Oki et al. (2001), Table 2, land-surface models and TRIP routing model, time period 1987–1988. |
| D03     | Doll et al. (2003), Table 1, model WGHM, time period 1961–1990. |
| G04     | Gerten et al. (2004), Table 2, model LPJ, time period 1961–1990. |
| N       | endorheic basins included. |
| X       | exorheic basins only. |

$^a$ Grid cell area and continental boundaries from Fekete et al. (1999b), endorheic basins included. These areas are only valid for the W estimate (F02 and F99bm is calculated for 1.6% fewer grid cells). Oceania is defined as Australia, New Zealand, Papua New Guinea and some small Islands. W simulation is only made for a minor part of Greenland, which is included in the North America values.

$^b$ It is assumed,that this estimate excludes endorheic basins (not clearly stated in the original publication).

$^c$ It is assumed that these estimates include endorheic basins (not clearly stated in the original publication).

Figure 3 Global average (1915–2000) runoff simulated with the WASMOD-M global water-balance model. The simulation is based on a parameter-value set tuned from 485 globally-distributed gauging stations. The dots indicate endorheic basin outlets.
It should be investigated if the difference between measurement-based and model estimates is related to different handling of ungauged basins. Oki et al. (1995) conclude in their global assessment that runoff is lower in ungauged than in gauged areas. Additionally, Fekete et al. (2002) report, by combining observation data and simulations with the WBM model, that the ungauged actively discharging areas are wetter than the gauged ones.

WASMOD-M has not been subjected to consistency tests such as parameter independency, heteroscedasticity, split-sample-proxy-basin test that the WASMOD catchment model has passed (Xu, 1999c), but few other global models present such results. One rare example is given by Nijssen et al. (2001b) in the test of their regionalisation algorithm, based on climatic zones. In this application of the model, we used less input data than other global models. The present version of WASMOD-M does not account for, e.g. time delays along river networks, evaporation losses from dams and rivers, flood inundation, anthropogenic water abstraction, river regulation, river routing, subgrid variability, glacier dynamics, permafrost and capillary rise. Future model development may include additional processes and input data if validation data and consistency checks can substantiate them.

Data problems

Comparison of global water-balance models is difficult because, in contrast to GCMs, there are no common definitions of data structure, content and quality, time periods and temporal resolution. Data-related problems can be divided into three classes: (i) geographical boundaries and positions, (ii) runoff- and precipitation-data quality, differing time periods, and spatial mismatch, and (iii) unknown or unavailable anthropogenic runoff influences.

Geographical boundaries and positions

There are several databases of global and continental river flow nets and/or runoff, e.g. STN-30p/GRDC (given by Fekete et al. (1999b) Hydro1k (USGS, 2004) and GHCDN (Dettinger and Diaz, 2000) and provided by NCAR (Bodo, 2001a,b). However, these commonly show differences in
routing, basin-area sizes, and boundaries. The positioning of gauging stations is not identical in different databases and the stations are sometimes given relocated longitude—latitude information to fit into the spatial resolution of the grid net (e.g. GRDC/STN-30p). Basin areas for given gauging stations can sometimes differ considerably (Renssen and Knoo, 2000), which causes problems in validation of digital river networks and results in different runoff estimates in model comparisons.

There are also different definitions and boundaries. Oceania, e.g. is defined by different sources as including or excluding parts of Australia, New Zealand, Papua New Guinea and various small islands (e.g. Niessen et al., 2001b). In addition to the border to Oceania, the borders of Asia with Europe often differ, e.g. by the assignment of Turkey (Niessen et al., 2001b; Döll et al., 2003). Arctic areas (especially Antarctica and Greenland) are commonly excluded in modelling studies but included in global compilations of runoff measurements.

Runoff from rivers to oceans (exorheic) makes up the major part of the global runoff. Other contributions come from groundwater flow to oceans, river flow to inland basins (endorheic) and groundwater flow to inland basins. Korzun et al. (1978) estimate the amount of river flow which evaporates and comes from percolation into rivers. It is not always clear which of these components are included in various global and continental runoff estimates (Table 2). Global runoff also varies with time (e.g. Shiklomanov, 1997) and not all estimates include information about the time period for the calculation (Table 2).

Inconsistent runoff and precipitation data and differing time periods

Combinations of precipitation and runoff data from different sources and time periods cause unreasonable runoff coefficients. Problems with runoff coefficients are reported previously (e.g. Fekete et al., 1999a; Niessen et al., 2001b). In contrast to Niessen et al. (2001b), who exclude the Yukon River in Alaska because of a too small runoff coefficient of 0.25, we found very high runoff coefficients ranging from 0.75 to 1.93 for most Alaskan basins. Like us, Niessen et al. (2001b) describe the neighbouring Brahmaputra and Irrawaddy basins as problematic, whereas we were not able to confirm their runoff coefficient problems in the Columbia River basin.

Although, problems with runoff coefficients are mostly caused by inconsistent data, some relate to model deficiencies. Negative runoff coefficients in interstation sub-basins can be caused by differing measuring techniques, anthropogenic water withdrawal, river-bed seepage and evaporation from open-water bodies in warm climates. Use of averaged runoff data from different time periods to calculate the runoff coefficient could also cause problems.

Unknown and unavailable anthropogenic runoff influences

Most hydrologic models mimic natural variations of water-balance components. Regulation of rivers by dams, re-routing of water to other basins, and water extraction are major anthropogenic influences that considerably disrupt the natural water balance. Vörösmaaty et al. (1997) and Nilsson et al. (2005) quantify the influence of dams and the degree of regulation of large rivers and find that dams globally impact 83% of the global runoff, and represent a 700% increase in the standing stock of natural river water, with residence times for individual impoundments spanning from one day to several years. Lehner and Döll (2004) elaborate a new global database of lakes, reservoirs and wetland, but we are still far away from a trustworthy global database of time series accounting for anthropogenic influences of the global water cycle. Hence, even a perfect fit between simulated and measured runoff needs to be evaluated critically and should not be overrated.

Global runoff estimates

WASMOD-M runoff simulations with the 'standard', i.e. the geographically-distributed best-fitting, parameter-value set produced global and continental runoff within the range of other models and measurement compilations (Table 2). Larger areas were simulated acceptably with WASMOD-M (Fig. 1) rather than with WGHM (see Fig. 2 in Döll et al., 2003), possibly as a consequence of WGHM simulating yearly runoff within ±1% of the measured, while the WASMOD-M limit was set to ±20%. Most areas that Döll et al. (2003) accept without correction were also accepted with WASMOD-M. WGHM simulates runoff acceptably in Rio Madeira in the Amazon basin and River Rhine, where WASMOD-M did not. More examples can be found of the opposite, e.g. in many northern basins, where WGHM underpredicts, but also in the Murray, Oranje and West African rivers. One explanation is that WGHM uses uncorrected precipitation input, causing an underestimation for snow-covered areas. Moreover, five parameters were tuned in WASMOD-M compared to one in WGHM.

Most other global models underestimate runoff in snow-covered areas (Macro-PDM — Arnell, 1999a; WBM — Fekete et al., 1999a; WGHM — Döll et al., 2003; TRIP with different land-surface models — Oki et al., 1999; LJP — Gerten et al., 2004), usually because of underestimated precipitation. At the same time most of these models overestimate runoff in arid basins, e.g. because open-water evaporation is not considered. In the study presented here, WASMOD-M did not follow these patterns, probably because of our parameter-value estimation.

The difference between the largest and smallest global runoff estimates in Table 2 exceeds the highest continental runoff estimate. The model estimates, including WASMOD-M’s, are generally lower than the estimates based only on measurements. The total simulated runoff with WASMOD-M included runoff to inland drainage basins, but excluded runoff from Antarctica and 89% of Greenland. It is comparable to the measurement compilation of L’vovich (1979) who only considers runoff to oceans, but higher than WBM (Fekete et al., 1999b), WGHM (Döll et al., 2003), VIC (Niessen et al., 2001b; Table 4) and the TRIP routing scheme combined with different land-surface models (Oki et al., 2001). On the other hand, it is lower than LJP (Gerten et al., 2004) and UNH/GRDC Composite Runoff Fields V1.0 (Fekete et al., 1999b). The low value of total simulated runoff reported by Oki et al. (2001) should partly be related to the short time period (1987—1988). WASMOD-M also simulates low runoff, 92% of the 1961—1990 average value, for this period.
Even if there is a general tendency that global runoff estimates based only on measurements are higher than modelled ones, there are at least three reasons why the difference should be even larger. Runoff to internal basins is commonly excluded in compilations of runoff measurements. The exorheic runoff simulated with WASMOD-M is equal to the runoff compiled from measurements by Baumgartner and Reichel (1975). There should also be a difference between those measurement compilations that include groundwater runoff into oceans and those that do not. Some of the measurement compilations include evaporation from rivers and dams, which is not included in any model with the exception of WGHM (Döll et al., 2003).

Continental runoff estimates of WASMOD-M were generally in the same range as previous estimates (Table 2), with the exception of a larger runoff from Europe and a lower runoff from South America. This could partly be explained for Europe where Döll et al. (2003) and Arnell (1999a) find the Willmott et al. (1998) precipitation-correction too high. For South America, we think that the difference was caused by problems in finding acceptable parameter values for the major part of the Amazon River basin without accepting unreasonably high land moisture values. South American runoff was higher when the land-moisture limitation was disregarded. The low runoff from Oceania was most likely caused by a limited continental area, since the WASMOD-M estimate only included Papua New Guinea, not the whole island of New Guinea. The combined WASMOD-M estimate from Asia and Oceania was in the same range as others.

### Runoff from selected basins

Comparison between observed and simulated within-year variations in runoff is complicated by river regulation. Nilsson et al. (2005) show that almost all large river basins are regulated and that it is difficult to get reliable time-series data on regulation. Since, our WASMOD-M simulations did not include time-delayed routing, this negatively influenced the capacity to mimic within-year variations in basins with monthly or yearly delays. Regulation effects and missing time-delayed routing likely cause a higher variation of the simulated runoff as compared to the measured runoff values.

WASMOD-M was reasonably successful in simulating the average within-year runoff variations (Fig. 4, Table 3) although it was only calibrated against average runoff. Nilsson et al. (2005) show that almost all large river basins are regulated and that it is difficult to get reliable time-series data on regulation. Since, our WASMOD-M simulations did not include time-delayed routing, this negatively influenced the capacity to mimic within-year variations in basins with monthly or yearly delays. Regulation effects and missing time-delayed routing likely cause a higher variation of the simulated runoff as compared to the measured runoff values.

### Table 3 Characteristics of runoff-gauging stations selected because of their occurrence in previous articles. The minimum regulation capacity is defined as the quotient of usable water amount, excluding non-usable bottom water to the discharge before any substantial human manipulations (Nilsson et al., 2005). Regulation capacity does not say anything about the actual operation of dams (Nilsson et al., 2005)

<table>
<thead>
<tr>
<th>Gauging station</th>
<th>River</th>
<th>Country</th>
<th>Area a (km²)</th>
<th>Start year</th>
<th>End year</th>
<th>Regulation capacity</th>
<th>Regulation delay b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norman Wells</td>
<td>Mackenzie</td>
<td>Canada</td>
<td>1,570,000</td>
<td>1966</td>
<td>1984</td>
<td>12%</td>
<td>1–3 months</td>
</tr>
<tr>
<td>Vicksburg</td>
<td>Mississippi</td>
<td>USA.</td>
<td>2,964,252</td>
<td>1965</td>
<td>1983</td>
<td>15.5%</td>
<td>1 week–1 month</td>
</tr>
<tr>
<td>Óbidos</td>
<td>Amazon</td>
<td>Brazil</td>
<td>4,640,300</td>
<td>1928</td>
<td>1996</td>
<td>3% (lumped with Orinoco)</td>
<td>1 week–1 month</td>
</tr>
<tr>
<td>Alcântara del Rio</td>
<td>Guadalquivir</td>
<td>Spain</td>
<td>46,995</td>
<td>1913c</td>
<td>1994</td>
<td>34%</td>
<td>1 week–1 month</td>
</tr>
<tr>
<td>MontJean</td>
<td>Loire</td>
<td>France</td>
<td>110,000</td>
<td>1863c</td>
<td>1979</td>
<td>1.5%</td>
<td></td>
</tr>
<tr>
<td>Borgharen</td>
<td>Maas</td>
<td>Netherlands</td>
<td>21,300</td>
<td>1911c</td>
<td>1990</td>
<td>5% (lumped with Rhine)</td>
<td></td>
</tr>
<tr>
<td>Tczew</td>
<td>Wisla</td>
<td>Poland</td>
<td>194,376</td>
<td>1900c</td>
<td>1994</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>Ceatal Izmail</td>
<td>Danube</td>
<td>Romania</td>
<td>807,000</td>
<td>1921</td>
<td>1985</td>
<td>4.6%d</td>
<td>1–7 days</td>
</tr>
<tr>
<td>Bakel</td>
<td>Senegal</td>
<td>Senegal</td>
<td>218,000</td>
<td>1904d</td>
<td>1989</td>
<td>24%d</td>
<td>1–3 month</td>
</tr>
<tr>
<td>Kinshasa</td>
<td>Congo</td>
<td>Congo</td>
<td>3,475,000</td>
<td>1903b</td>
<td>1983</td>
<td>0%</td>
<td>1–7 days</td>
</tr>
<tr>
<td>Igarka</td>
<td>Yenisey</td>
<td>Russia</td>
<td>2,440,000</td>
<td>1936</td>
<td>1995</td>
<td>18%d</td>
<td>1–3 months</td>
</tr>
<tr>
<td>Bahadurabad</td>
<td>Brahmaputra</td>
<td>Bangladesh</td>
<td>636,130</td>
<td>1969</td>
<td>1992</td>
<td>8% (lumped with Ganges)</td>
<td>1–7 days</td>
</tr>
<tr>
<td>Huayankou</td>
<td>Huang He (Yellow R.)</td>
<td>China</td>
<td>730,036</td>
<td>1946</td>
<td>1988</td>
<td>51%d</td>
<td>6–12 months</td>
</tr>
<tr>
<td>Datong</td>
<td>Chang Jiang (Yangtze)</td>
<td>China</td>
<td>1,705,383</td>
<td>1923</td>
<td>1986</td>
<td>12%d</td>
<td>1–3' months</td>
</tr>
<tr>
<td>Stolb</td>
<td>Lena</td>
<td>Russia</td>
<td>2,460,000</td>
<td>1978</td>
<td>1994</td>
<td>3%</td>
<td>1–3 months</td>
</tr>
</tbody>
</table>

---

a Areas taken from GRDC, distributed through Fekete et al. (1999b).

b Vörösmarty et al. (1997).

c The measured data are averages from a longer time period than the simulated (starting 1915).

d These values are minimum values as dam data-collection was stopped because the rivers fell into the highest biological impact class (Nilsson et al., 2005).


f Before completion of the Three Gorges Dam project.
were set by regionalisation, which explained the poor simulation results. Good simulations could be achieved for both stations when too high state-variable values were accepted.

Conclusions

A global water-balance model, WASMOD-M, was constructed on the basis of the well-tested WASMOD catchment model. WASMOD-M is characterised by a simple structure and a small number of tuneable parameters, but may still be over-parameterised when considering the availability of global input and validation data. WASMOD-M was successful in temporally and spatially reproducing global and continental runoff with a parameter-value estimation procedure that was primarily intended to produce regionalised parameter values. It was not possible to simulate continental runoff with a single, globally-uniform parameter-value set, but a continentally-uniform set for each continent was sufficient for acceptable results. A distributed parameter-value set was needed to correctly simulate individual basins.

Parameter values were estimated for individual basins and the set of acceptable parameter-value sets achieved this way was used to regionalise parameter values to the 50% of the world land surface lacking globally consistent runoff data. We suggest that an international collaboration should be established to compare runoff estimates from models and measurement compilations for all ungauged basins of the world. Such collaboration should identify common definitions of basin and continental areas and runoff measures as well as inclusion or exclusion of endorheic runoff, groundwater seepage, etc. to allow for unambiguous comparisons.

Global water-balance modelling is primarily constrained by data. Thus, a stronger focus on international collaboration is needed on global and continental databases. High-quality precipitation data (see, e.g. the local evaluations of Achberger et al., 2003) are especially needed to decrease the uncertainty in global and continental water balances. Improved data on anthropogenic runoff modifications are also much needed to evaluate model skill in capturing within-year patterns.

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