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A global comparison of four potential evapotranspiration equations and their relevance to stream flow modelling in semi-arid environments

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Abstract. This study compares four different potential evapotranspiration equations according to Priestley Taylor, Kimberly Penman, Penman Monteith (FAO-56) and Hargreaves on a global basis to demonstrate their difference, and assess their impact on the calculation of stream flows. The various equations of potential evapotranspiration show great differences in magnitude. But due to the limited availability of validation data, it is difficult to assess which method is the physically most reasonable to be applied. According to this study, the radiation-based Priestley Taylor equation proved to be most suitable for a global application. For the calculation of stream flows, however, the processes involved in the derivation of actual evapotranspiration values from potential evapotranspiration values appear more relevant than the absolute value of the potential evapotranspiration itself.

1 Introduction

Limited availability of measured climate and discharge data sets for semi-arid and arid areas restricts the reliability of global hydrological modelling in these regions. Validation with available runoff data sets shows an overestimation of the discharge in semi-arid to arid regions for various global hydrological models (Fekete et al., 1999; Nijssen et al., 2003 as cited in Döll et al., 2003). Due to several reasons (Döll et al., 2003), the quantitative simulation of the discharge can lie outside acceptable limits: (1) The quality of the input data sets highly influences the quality of the simulations. Secondly, a grid-based simulation will not concur with point measurements due to spatial and temporal averaging of input data and processes. (3) Further uncertainty arises from the fact that the selection of representative processes might not be complete and important processes might be ignored. (4) Processes itself might be reproduced with inadequate algorithms. In this study, potential evapotranspiration is examined with respect to the latter case, while the generation of river discharge in semi-arid areas is analysed with respect to case (3).

Evapotranspiration as a major component of the water balance has been identified as a key factor in hydrological modelling and a wealth of methods have been developed for its calculation (see for example Brutsaert, 1982; Jensen et al., 1990). As a first attempt to improve stream flow simulations in semi-arid and arid areas, the global applicability and results of four potential evapotranspiration equations are compared in magnitude, as well as in their impact on stream flow simulations for the six-year period of 1990–1995. Further, a semi arid to arid study region in the Middle East is chosen to compare calculated potential evapotranspiration values to Class A Pan measurements, and to carry out a model-intercomparison where actual evapotranspiration simulations of a global hydrology model are compared to results from a physically-based regional model that has been developed with special focus on vertical water-fluxes.

2 Materials and methods

2.1 Equations of potential evapotranspiration

In general, the terms potential evaporation and potential evapotranspiration are to be differentiated. The first is a measure for the atmospheric demand, which is solely meteorologically driven under the assumption of unlimited water supply. The latter combines the rate at which water is removed from wet soils with that from plant surfaces under unlimited water supply. Especially for irrigation scheduling, this definition was further specified to refer to a reference surface consisting of a hypothetical grass with

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specific characteristics, termed reference crop evapotranspiration (Allen et al., 1998; Wright, 1981; Doorenbos and Pruitt, 1977; Penman, 1956). Empirical crop coefficients are used to relate the reference crop evapotranspiration to crop evapotranspiration under non-standard conditions (Allen et al., 1998). It has, however, become common practice to use the terms potential evaporation and potential evapotranspiration interchangeably in the literature despite their different definition in terms. We will compare the output of various potential evapotranspiration equations on a global basis.

Noteworthy definitions of potential evaporation include the radiation-based formulation of Priestley and Taylor (1972), which is termed reference crop evapotranspiration by Jensen et al. (1990) and Maidment (1992):

$$E_p = \alpha_{\mathrm{PT}}(\frac{\Delta}{\Delta + \gamma})(R_N - G)[\mathrm{mm/d}] \quad (1)$$

with R_N=net radiation [mm/d], G=soil heat flux [mm/d] (can be neglected according to Maidment, 1992), Δ=gradient of saturated vapour pressure [kPa/°C], and γ= psychrometric constant [kPa/°C]. The α_{PT} factor [–] has the value of 1.26 and accounts for the aerodynamic component. Jensen et al. (1990) showed that the value of 1.26 is valid for humid areas, only. For arid areas, the value of 1.7 to 1.75 is more appropriate, in order to account for advection. We will compare the influence of a constant α_{PT}=1.26 (“PT 1.26”) and the differentiation into humid and arid areas with α_{PT}=1.26, and 1.74, respectively (“PT”), as suggested by Maidment (1992).

Penman (1948) was the first to introduce a combination equation to calculate reference crop evapotranspiration, termed this way as it combines the theoretical energy balance with the mass transfer method (Burman and Pochop, 1994). Here, we use the modified Kimberly Penman (“KP”) version to calculate reference crop evapotranspiration for alfalfa (Wright, 1982), which additionally features a seasonally variable wind function. The wind function is used as cited in Allen et al. (1989).

$$E_p = \frac{R_N \Delta}{\Delta + \gamma} + \left(\frac{6.43_\gamma W_f d}{\Delta + \gamma}\right) / \lambda[\mathrm{mm/d}] \quad (2)$$

with d=vapour pressure deficit [kPa], W_f=wind function, λ=latent heat of vaporization [MJ/m^{2}d], all other parameters as defined in (1). The wind function takes the form

$$W_f = (a_w + b_w u_2) \quad (3)$$

with u_2=wind speed at 2 m [m/s],

$$a_w = 0.4 + 1.4 \exp[-((J - 173)/58)^2] \quad (4)$$

$$b_w = (0.007 + 0.004 \exp[-((J - 2432)/80)^2)])(86.4) \quad (5)$$

where J is the Julian day of the year. In southern latitudes, J is incremented or decremented by 183, respectively (Allen et al., 1989).

Another extension of the Penman equation is the Peman-Monteith equation, which will be applied in the FAO 56 recommended form (Maidment, 1992):

$$E_P = \frac{R_N \Delta}{\Delta + \gamma} + \left(\frac{\gamma u_2}{\Delta + \gamma}\right)\left(\frac{r}{T + 273}\right)[\mathrm{mm/d}] \quad (6)$$

with T=air temperature [°C] and r=resistance term [–]. The aerodynamic and surface resistances of the original Penman Monteith equation have been set according to the particular reference crop and are included in the constant number r, which has a value of 900 for grass (“PM grass”) and 1600 for alfalfa (“PM alfalfa”) (Maidment, 1992). All other parameters apply as defined in (1) and (3).

The temperature-based evapotranspiration equation defined by Hargreaves et al. (1985) is further applied in this study (“HG”). It is solely temperature-based and was initially developed for the semi-arid and arid area of California.

$$E_P = 0.0023 S_0 \sqrt{\delta_T}\,(T + 17.8) \quad (7)$$

with S_0=water equivalent of extraterrestrial radiation [mm/d], T=air temperature [°C], δ_T=daily air temperature range [°C]. δ_T accounts for effects of cloudiness, correlates with relative humidity and vapour pressure and negatively with wind speed (Hargreaves and Allen, 2003). The authors make no comment for the case of $T \leq -17.8$°C, which is necessary for a global application. In this case, E_P is set to zero.

Many other equations could not be applied globally, because for certain days of the year, the equations are mathematically not defined and the authors give no recommendations for these cases. This clearly results from the fact that most equations were developed for a specific climatic region, or specific time of the year (e.g. growing season for reference crop evapotranspiration). For example, the Turc method is valid for temperatures above 0°C and for humid climates, only (Maidment, 1992; DVWK, 1996). The Thornthwaite method is only recommended for monthly sums of evapotranspiration and has been demonstrated to give unrealistic values for Europe (DVWK, 1996).

For simplicity, the output of Eqs. (1), (2), (6), and (7) will be termed potential evapotranspiration. For its calculation, only the grid-routine of the WaterGAP model (refer to Sect. 2.1) is used, consisting of 66 896 grid cells. No model specific procedures are relevant for the results; they solely depend on the input data and the chosen equations. For the input data we rely on the CRU TS 2.1 gridded climate data set that provides time series of monthly precipitation, air temperature, cloud cover and wet day frequency (Mitchell and Jones, 2005). Wind information, when applicable, was used from the long-term average gridded climatology data set CRU CL 1.0 (New, 1999). In this study, only evaporation and transpiration from the land fraction of a cell is considered, as evaporation from open waters (e.g. lakes and wetlands) is not included in the above definitions and its calculation is based on slightly different fundamentals. The evaluation period is 1990–1995.

2.2 The global model

The analysis is based on one of the current state-of-the-art global hydrological models, WaterGAP (Water-Global Assessment and Prognosis), which computes current and future water availability and water use (Alcamo et al., 2003; Döll et al., 2003). For calculations of water availability, the daily vertical water balance (Fig. 1) is calculated for each grid cell ($0.5^{\circ} \times 0.5^{\circ}$ geographical latitude and longitude). In a standard run, potential evapotranspiration is calculated according to Priestley Taylor. The distinction between arid and humid after Jensen et al. (1990) foresees a classification based on the month with the peak evapotranspiration at the arbitrary threshold of a relative humidity of 60%. Since the month with the peak evapotranspiration cannot be determined prior to the calculation itself, a classification based on land cover is implemented in WaterGAP, where grassland/steppe, hot desert, scrubland, and savanna are considered as arid, the remaining land cover classes are humid. From the potential evapotranspiration, actual evapotranspiration is derived based on a canopy and soil water balance. Potential evapotranspiration is hereby reduced according to the ratio of current canopy water storage to maximum canopy water storage based on an internally calculated leaf area index. Interception evaporation occurs as long as the canopy water storage is greater zero. Soil evapotranspiration is derived in a similar way based on the level of soil moisture saturation, which is a function of soil and vegetation specific field capacity. From the throughfall, which is precipitation reduced by interception, groundwater storage and surface runoff are calculated. The latter is routed through the respective river basin according to a global drainage direction map (Döll and Lehner, 2002) to form river discharge. WaterGAP is calibrated and validated against measured discharges from the Global Runoff Data Centre (GRDC, 2004). As climate input we use the CRU TS2.1 gridded climate dataset (Mitchell and Jones, 2005). Further, the FAO Soil Map of the World (FAO, 1995) is used, as well as the global land cover grid as modelled by IMAGE 2.1 (Alcamo, 1998). Further input is specified in Döll et al. (2003).

2.3 The regional model

TRAIN (Menzel et al., 2007) is a physically-based, spatially distributed model which includes information from comprehensive field studies on the water and energy balance of various land cover types, including natural vegetation and agricultural land. It has been designed to simulate the individual water budget components at different spatial and temporal scales with focus on the soil-vegetation-atmosphere interface. The vertical water fluxes are calculated as follows: evapotranspiration follows the Penman Monteith equation (Monteith, 1965), interception is simulated according to Menzel (1997), and the calculation of the soil water balance and percolation follow a modified version of the conceptual approach from the HBV-model (Bergström, 1995). The application of TRAIN for agricultural land includes an automated irrigation process. When the soil water content falls below a critical limit, the model assumes irrigation until field capacity is reached. Since the model is especially designed to simulate vertical water fluxes in great detail, horizontal water flow from one cell to another is not considered. The model was initially developed for the humid environments of Central Europe and has been extensively validated with experimental data (e.g., actual evapotranspiration data determined with micrometeorological methods or lysimeter measurements) (Menzel, 1999). It is currently adapted to the arid and semi-arid regions of the Jordan River: The major land-use types of the region and their typical annual development were introduced as well as some basic irrigation practices in agriculture. The model has been validated with data from several experimental sites along the climatic gradient (Sect. 2.4) covered with natural vegetation, forest and agricultural crops. A first application of TRAIN to the region can be found in Menzel et al. (2007).

For this study, TRAIN was run with a temporal resolution of one day and a spatial resolution of 18 km×18 km (see Fig. 2) based on the resolution of the climate input. Meteorological time series (precipitation, air temperature, air humidity, wind speed and solar radiation) were used as calculated by the regional climate model MM5 (2007) from the Institute for Meteorology and Climate Research IMK-IFU. The assumed land cover came from the Global Land Cover Characterization (USGS, 2007). Further input data is described in Menzel et al. (2007). The following table (Table 1) compares the main elements of the two models as they have been applied in this study.

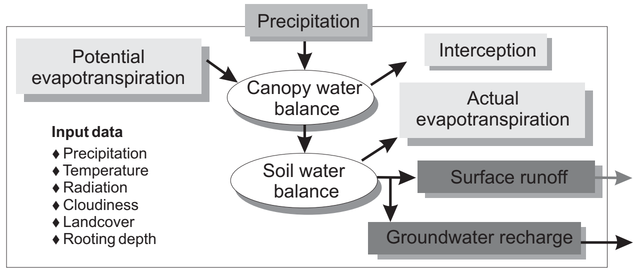

Fig. 1. Schema of the daily vertical water balance that is calculated for each grid-cell in WaterGAP.

2.4 The regional study area

The study region (Fig. 2), situated in the area of the Jordan River, is one of the most critical regions of current and future water scarcity. The strong climatic gradient from sub-humid in the north to arid in the south condenses many different climatic conditions into a small region, which turns this area into a unique study region with high transferability of results gained here. This strong climatic gradient is also an

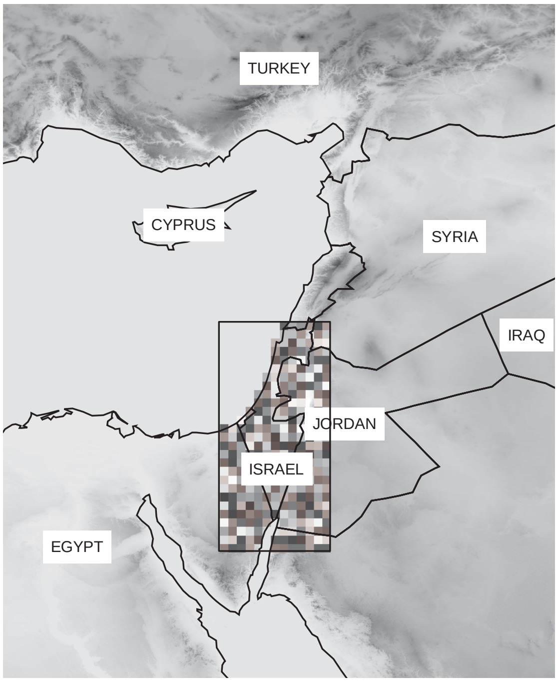

Fig. 2. TRAIN simulation grid in the semi-arid to arid study region, situated at the Jordan River.

Table 1. Comparison of the main features of the global model (WaterGAP) and the regional model (TRAIN).

Feature	WaterGAP	TRAIN
Spatial resolution	0.5°×5° isogonal	18 km×18 km isometric
Spatial coverage	global	regional
Climate input	CRU TS 2.1	MM5
Land cover input	IMAGE	GLCC
Potential evapotranspiration equation	Priestley Taylor	Penmann Monteith
Irrigation	not assumed	based on expert knowledge

important factor for water availability. Sources of water are concentrated in the north of the region. The main precipitation falls during winter (November–January), with approximately 800 mm/ year in the north and 100 mm/year in the south. The Jordan River and its aquifers are trans-boundary resources, and the scarcity of water is used as a political issue between rivalling states.

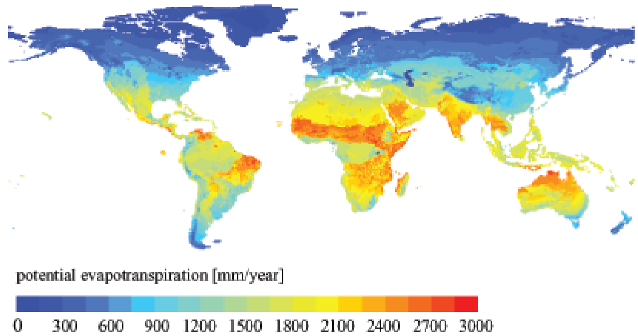

Fig. 3. Average annual potential evapotranspiration (1990–1995) of land areas based on the Priestley Taylor equation with a variable α_{PT} for humid (1.26) and arid (1.74) areas.

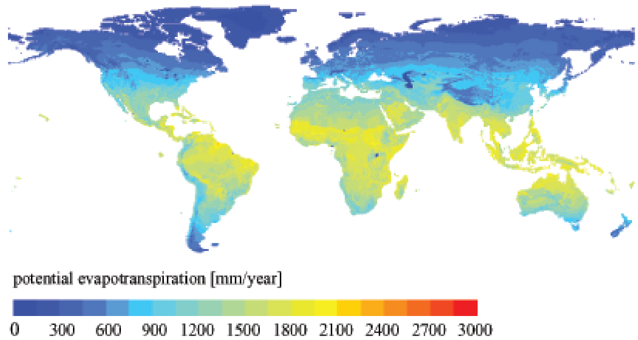

Fig. 4. Average annual potential evapotranspiration (1990–1995) of land areas based on the Priestley Taylor equation with α_{PT}=1.26.

3 Results: Comparison of potential evapotranspiration values

3.1 Intercomparison of different potential evapotranspiration equations

Figures 3 to 8 show average annual sums of potential evapotranspiration calculated with Eqs. (1) to (7). Lakes are depicted in blue because evaporation from open water is not calculated in this study. It appears that the Priestley Taylor (Fig. 3) equation yields the highest values of evapotranspiration. The distinction between arid and humid areas can be recognized in a mosaic-like structure, where very high potential evapotranspiration values are calculated for arid areas due to the α_{PT}-factor. For a constant α_{PT}=1.26, lower values as shown in Fig. 4 result.

The Kimberly Penman equation led to the second highest potential evaporation values (Fig. 5) of all methods applied. Noteworthy are the elevated values in northern South America and the Congo basin, and higher values in Europe, in comparison to the Priestley Taylor equation with a variable α_{PT}.

The evaluation of the FAO 56 Penman Monteith equation, both for reference grass and alfalfa evapotranspiration (Fig. 6

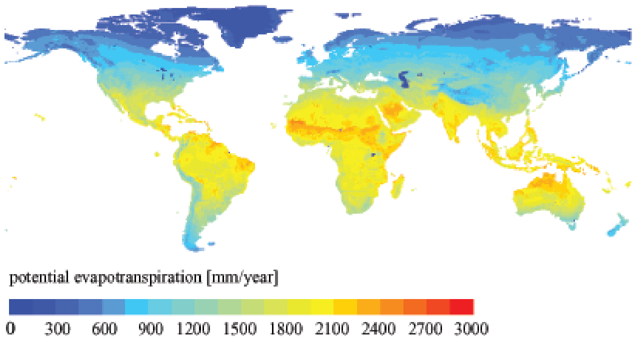

Fig. 5. Average annual potential evapotranspiration (1990–1995) of land areas based on the Kimberly Penman equation.

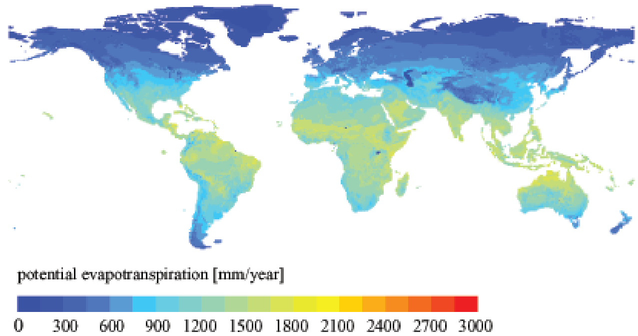

Fig. 7. Average annual potential evapotranspiration (1990–1995) of land areas based on the FAO 56 Penman Monteith equation for alfalfa.

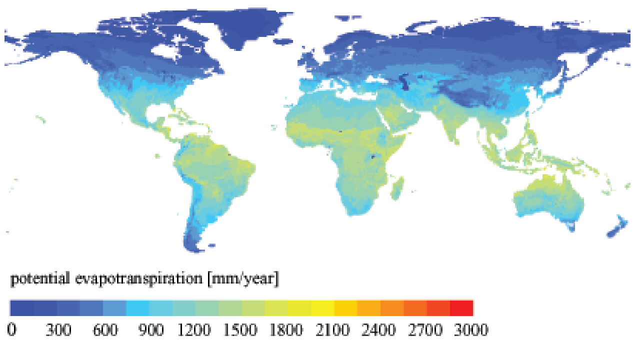

Fig. 6. Average annual potential evapotranspiration (1990–1995) of land areas based on the FAO 56 Penman Monteith equation for grass.

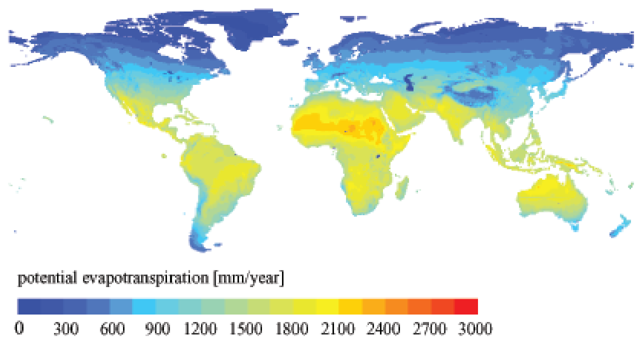

Fig. 8. Average annual potential evapotranspiration (1990–1995) of land areas based on the Hargreaves equation.

and 7) showed unexpected low values, especially when compared to a study by Droogers and Allen (2002), who evaluated the same equation for grass based on CRU CL data (long term monthly averages 1961–1990) and obtained values nearly twice as high.

The Hargreaves equation led to overall higher values than Priestley Taylor (arid/humid based on landcover) except for those areas classified as arid (Fig. 8). Remarkable is the temperature-based cloud-like pattern of evaporation zones. The lag of peak estimates has to be noted with this equation, which becomes visible when looking at daily or monthly values due to the lag of temperature in comparison to radiation, which was also found by Jensen et al. (1990).

A comparison of the absolute values of potential evapotranspiration calculated with the various equations for the GEO4 regions (UNEP, 2007) is shown in Fig. 9.

3.2 Comparison of calculated potential evapotranspiration values to measured pan evaporation data in the study region

Currently, no consistent global data set is available to validate potential evapotranspiration. For a first approximate comparison, pan evaporation data from 23 Class A pan measuring stations in the Jordan River region are compared to simulated data at each of the locations. The measured data was available in monthly or daily resolution. It was aggregated to yearly values and then averaged over a minimum of 5 years, whereby the evaluation period could not be limited to the years 1990–1995 due to lack of data. Instead, values between 1980 and 2005 were used under the assumption that a general change of local evapotranspiration values over the decades can be neglected.

Figure 10 shows the WaterGAP grid for the study region and the location of the pan measuring stations. Preferably, the average over a number of stations should be compared to the respective grid-cell value, which itself can only represent an average (see Sect. 1, bullet 2). Unfortunately, too little data was available and most of the grid cell values are compared to single point measurements. Therefore, exact matches are not expected. Table 1 contains (averaged) pan evaporation measurements, corrected (averaged) pan evaporation measurements, the number of stations over which this value was averaged, and the calculated values based on Eq. (1) to (7).

Problems with pan evaporation measurements arise from the difficulty of accurate measurements during rainfall, or poor maintenance of the pan causing inaccurate

Table 2. Comparison of average annual (1990–1995) measured pan evaporation rates versus calculated potential evapotranspiration, and percentage deviation of calculated value from corrected measured values, with avg. pan=average measured Class A pan evaporation, corr. pan=corrected pan evaporation, PT=Priestley Taylor with α_{PT}=1.74 in arid areas and αPT=1.26 in humid areas, PT 1.26=Priestley Taylor with a constant α_{PT}=1.26, PM grass=Penman Monteith grass reference evapotranspiration, PM alfalfa=Penman Monteith alfalfa reference evapotranspiration, KP=Kimberly Penman, and HG=Hargreaves.

Grid cell	Avg. pan [mm]	Corr. pan (*0.7)	No. of pan stat.	PT [mm]	PT [%]	PT 1.26 [mm]	PT 1.26 [%]	PM grass [mm]	PM grass [%]	PM alfalfa [mm]	PM alfalfa [%]	KP [mm]	KP [%]	HG [mm]	HG [%]
A2	2069.3	1448.5	2	1877.7	(29.6)	1359.7	(–6.1)	1154.4	(–20.3)	1193.0	(–17.6)	1727.8	(19.3)	1352.8	(–6.6)
A3	2729.2	1910.5	1	1844.3	(–3.5)	1335.6	(–30.1)	1137.3	(–40.5)	1180.2	(–38.2)	1711.5	(–10.4)	1480.9	(–22.5)
A7	3589.6	2512.7	1	1605.0	(–36.1)	1162.3	(–53.7)	1008.5	(–59.9)	1062.0	(–57.7)	1640.8	(–34.7)	1579.9	(–37.1)
B2	2217.2	1552.1	3	1898.4	(22.3)	1374.7	(–11.4)	1160.0	(–25.3)	1196.5	(–22.9)	1734.0	(11.7)	1339.6	(–13.7)
B3	2456.7	1719.7	1	1473.4	(–14.3)	1066.9	(–38.0)	925.3	(–46.2)	968.0	(–43.7)	1503.2	(–12.6)	1490.4	(–13.3)
B5	3541.7	2479.2	1	1523.4	(–38.6)	1103.1	(–55.5)	954.0	(–61.5)	1001.3	(–59.6)	1575.0	(–36.5)	1591.8	(–35.8)
C1	1973.8	1381.6	2	1971.2	(42.7)	1427.4	(3.3)	1199.6	(–13.2)	1233.2	(–10.7)	1771.8	(28.2)	1381.0	(0.0)
C2	2404.6	1683.2	2	1979.8	(17.6)	1433.7	(–14.8)	1208.3	(–28.2)	1246.2	(–26.0)	1802.4	(7.1)	1422.5	(–15.5)
C3	2479.2	1735.5	1	1498.0	(–13.7)	1084.8	(–37.5)	930.7	(–46.4)	970.0	(–44.1)	1519.1	(–12.5)	1436.6	(–17.2)
C4	3169.5	2218.7	1	1561.9	(–29.6)	1131.0	(–49.0)	976.6	(–56.0)	1022.5	(–53.9)	1596.5	(–28.0)	1570.8	(–29.2)
D1	2342.2	1639.5	2	1577.7	(–3.8)	1142.5	(–30.3)	983.6	(–40.0)	1023.0	(–37.6)	1581.8	(–3.5)	1473.8	(–10.1)
D2	2017.4	1412.2	2	1958.2	(38.7)	1418.0	(0.4)	1194.8	(–15.4)	1234.1	(–12.6)	1783.4	(26.3)	1396.0	(–1.1)
E2	1767.9	1237.5	1	1495.9	(20.9)	1083.3	(–12.5)	934.2	(–24.5)	978.1	(–21.0)	1521.1	(22.9)	1428.3	(15.4)
F2	3602.7	2521.9	1	1532.6	(–39.2)	1109.8	(–56.0)	962.7	(–61.8)	1013.4	(–59.8)	1566.9	(–37.9)	1520.2	(–39.7)
F3	3589.6	2512.7	1	1605.0	(–36.1)	1162.3	(–53.7)	1008.5	(–59.9)	1062.0	(–57.7)	1640.8	(–34.7)	1579.9	(–37.1)
G1	4831.9	3382.3	1	1631.2	(–51.8)	1181.2	(–65.1)	1036.4	(–69.4)	1097.9	(–67.5)	1676.2	(–50.4)	1575.4	(–53.4)
Avg. deviation [%]					(–5.9)		(–31.9)		(–41.8)		(–39.4)		(–9.1)		(–19.8)

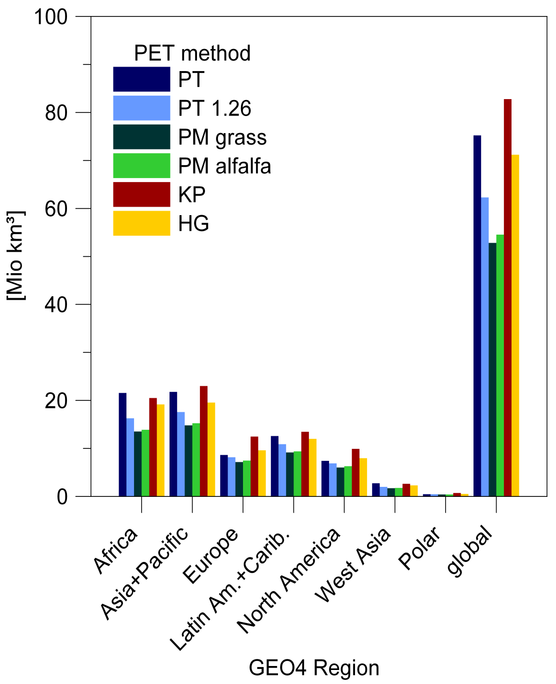

Fig. 9. Global and regional potential evapotranspiration (PET) sums based on various methods for the GEO4 regions.

measurements (Bloemen, 1978 as cited in Linacre, 1994). In general, pan evaporation measurements are of higher magnitude than reference crop evapotranspiration (Jensen et al., 1990). According to Linacre (1994), they can be adapted by using a correction factor of the value of 0.7, which was applied to the measured values.

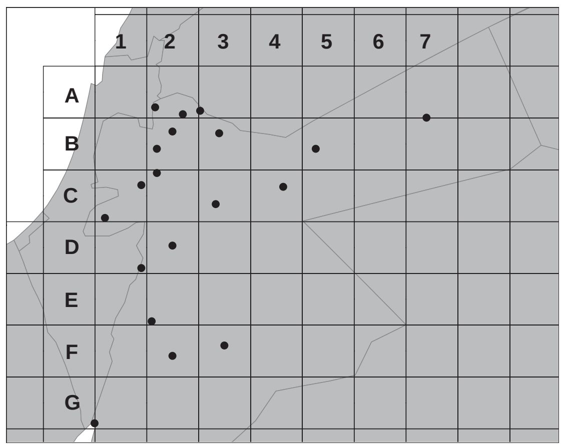

Fig. 10. WaterGAP grid with Class A pan evaporation measurement locations in the study region.

All calculated values stay well below measured values. If compared to the corrected measurements, the Priestley Taylor method with a variable α_{PT} for arid and humid areas shows the best results with an averaged deviation of –5.9% in the examined study region. The second closest calculation was obtained with the Kimberly Penman method with a deviation of –9.1%. Hargreaves method showed a deviation of –19.8% whereas Priestley Taylor with a constant $\alpha_{PT}$of 1.26, and Penman Monteith FAO 56 showed deviations of –30%––40%.

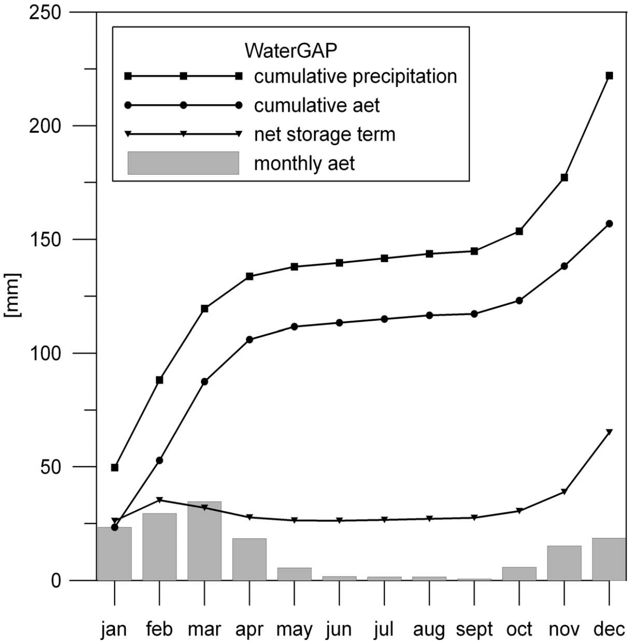

Fig. 11. 1961–1990 long-term average monthly water balance as calculated with WaterGAP for the TRAIN simulation grid, with cumulative aet=cumulative actual evapotranspiration, net storage term=cumulative precipitation–cumulative aet.

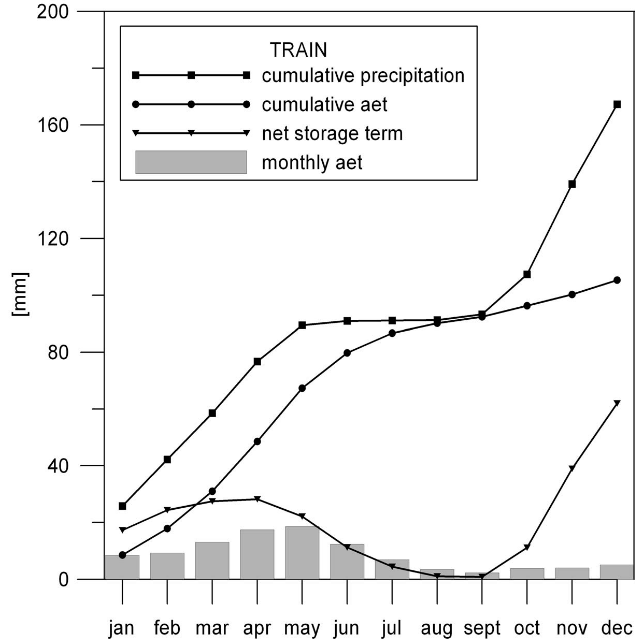

Fig. 12. 1961–1990 long-term average monthly water balance as calculated with TRAIN for the TRAIN simulation grid, with cumulative aet=cumulative actual evapotranspiration, net storage term=cumulative precipitation–cumulative aet.

3.3 The impact of different potential evapotranspiration equations on the stream flow simulation

The comparison with pan evaporation measurements suggests that the currently implemented algorithm for the calculation of the potential evapotranspiration according to Priestley Taylor produces the most reasonable results. This comparison was, however, restricted to a rather small study region. For the overall aim of improving stream flow calculations and a wider approach, the above-described potential evapotranspiration equations were utilized in WaterGAP runs for the calculation of stream flows, which were then validated with measured runoff data form the Global Runoff Data Centre (GRDC, 2004). In this comparison we were not able to detect a consistent improvement of modelled river discharges in 14 evaluated catchments. In humid areas, where the simulation of stream flow is good in general, no effect on the river discharge was noted under application of the various potential evapotranspiration equations. In semi arid and arid catchments, an impact on the modelled stream flow was visible but the equation that caused the closest agreement of simulated with measured stream flow data was a different one for the different catchments. Overall, none of the equations was capable to improve the calculated river discharges effectively. Therefore we conclude that it is very worthwhile to further examine the algorithms involved in the derivation of actual evapotranspiration values from potential evapotranspiration values.

4 Comparison of long-term average monthly actual evapotranspiration as calculated with a global and a regional model

Since potential conditions are only met during and shortly after precipitation, condensation or on irrigated fields (ASCE, 1996), the amount of actual evapotranspiration, which describes the evapotranspiration that occurs under natural constraints, is more relevant to the global modelling of the hydrological cycle. Actual evapotranspiration is usually calculated model-specifically from potential evapotranspiration based on various storage balances, taking into account plant parameters and field capacities.

In order to make a first attempt in assessing the performance of this calculation with the WaterGAP model in the study region, actual evapotranspiration rates were compared to those calculated with the regional model TRAIN. With the aim of facilitating the comparison of two models that rely on different algorithms and input data, we compare long-term average monthly (1961–1990) cumulated values and the overall behaviour of functions over the extend of the TRAIN simulation grid (Fig. 2). In Figs. 11 and 12, grey bars depict the long-term regional average monthly actual evapotranspiration values from the (1961–1990) WaterGAP and TRAIN runs (“monthly aet”). It has to be noted that in TRAIN, irrigation is included, which is treated similar to precipitation input. Further, the cumulative precipitation curve (“cumulative precipitation”) and cumulative actual evapotranspiration ("cumulative aet") curves are shown. The "net storage term" is the remainder of the cumulative balance of precipitation minus actual evapotranspiration and is thus composed of soil water and surface runoff. These two processes have to be regarded as one in this comparison because in TRAIN the horizontal water balance is not accounted for.

It appears that the actual evapotranspiration in WaterGAP is strongly correlated to precipitation with a priority on discharge generation over evapotranspiration generation. Calculations of actual evapotranspiration with TRAIN are stronger related to the level of soil water storage with emphasis on the vertical water fluxes as the horizontal water balance is not considered. The net storage term almost completely falls dry in the TRAIN simulations while the net storage term in the WaterGAP simulations remains above an average threshold of 25mm. This indicates that the calculated values of actual evapotranspiration in WaterGAP are too small, which could explain the overestimation of discharge values in semi-arid and arid catchments that was also found by Döll et al. (2003) for this model.

5 Discussion and conclusions

In this study we compared four different formulations for the calculation of potential evapotranspiration on a global basis. We applied one radiation-based method (Priestley Taylor), two combination equations (Kimberly Penman and Penman Monteith) and one temperature-based method (Hargreaves), which all showed great differences in magnitude. Due to the fact that the radiation-based equation showed the closest agreement with Class A pan evaporation measurements for a semi-arid study region, and for its overall low input requirements we found this equation to be most appropriate in the global application.

It has, however, to be noted, that the evaluation with measured data was carried out for a, although covering a large climatic gradient, small study region, with a rather low density of measuring stations. Also of the four applied potential evapotranspiration equations that yield an upper limit of potential evapotranspiration, three were initially developed for irrigation scheduling and therefore perform best for agricultural areas. Usually, empirical crop coefficients are used to relate the reference crop evapotranspiration to non-standard conditions. We have neglected the usage of these coefficients because they are not available for the variety of global land cover types and because crop coefficients for various agricultural areas have a value close to 1.0, with values below 1.0 for the most part of the growing season. We therefore assume that these differences are not significant in comparison to the large differences due to the different potential evapotranspiration equations used.

Further, the application of the two combination equations relies on wind data, which had to be taken from a climatology data set, as time series in the required resolution of 0.5 degrees are not yet available. This impairs the performance of the combination equations as the wind function is degraded to a wind factor. The combination equations might therefore lead to improved values if an appropriate wind product is available. This, however, further underlines the current advantages of the application of a radiation-based equation.

Since in most parts of the world, the process of evapotranspiration is rather water-limited as opposed to radiation-limited, the processes involved in deriving values of actual evapotranspiration from potential evapotranspiration is of higher relevance to the simulation of surface runoff and stream flows than the initial magnitude of the potential evapotranspiration itself. To date, too little process-knowledge is available turning the calculation of actual evapotranspiration into a model-specific process, related to various storage balances. Therefore a comparison between two models was carried out, where a global hydrological model was compared to a regional model. Both rely on different process algorithms and different input data that are both physically-based descriptions of the current state. The comparison of the behaviour of the storage functions revealed that it is worthwhile to examine the various storage balances in more detail rather than varying the potential evapotranspiration equations in order to improve stream flow simulations in semi-arid environments.

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