A continental scale water balance model: a GIS-approach for Southern Africa

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Abstract

A distributed GIS-based hydrological model is developed using GIS and computational hydrology techniques. The model is based on water balance consideration of the surface and subsurface processes. The surface water balance processes include precipitation infiltration, overland runoff, evapo-transpiration and canopy surface interception losses on daily time steps; The subsurface process considers soil moisture accounting on a monthly basis. The model was used to estimate generated runoff from matrix of specific geo-referenced grids representing Southern Africa. All regional and seasonal dispensation of water balances have been based on standard GIS formats for storage, spatial display and interpretation of results. Considering the 1961–1990 climatic period, we have mapped the regional variation of the mean annual soil moisture (SM), actual evapo-transpiration (AET), and generated runoff (ROF) across Southern Africa or known as the SADC region. The model estimates the mean SM of the region to be about 148 mm/year. There is a wide spatial range in the distribution of SM over the region due to the fact that the absolute soil moisture is dependent on the water retention properties of the soils considered across the region. The model prediction of the mean annual AET in the region reaches a maximum of 1500 mm, with mean 420 mm. The mean annual generated runoff from the land catchment in the region is about 151 mm/year although there is a significant inter-regional variation among the SADC countries, which is a function of the variation in the vegetation cover, soil and climate variation. Lower runoff regimes are dominant in arid areas in Botswana, Namibia and south-western part of the Republic of South Africa. Higher runoff regimes are the Northern and Western Tanzania, along the east coastal portions of Mozambique, central Mozambique, western Zambia and Malawi.

Keywords: Water balance model; GIS; Regional hydrology; Southern Africa; Runoff; Soil moisture; Evapo-transpiration

1. Introduction

Water balance models have been widely used to simulate regional water balances and to study hydrologic effect of climatic change. The Thornthwaite and Mather (1957) conceptualisation of the catchment water balance for long term monthly climatic condition has become one of the outstanding research areas of water balance modeling of a catchment, region or of a continent. Typical examples are (1) a grid-based model for Latin America of Vorosmarty et al. (1989); (2) the Rhine flow model of Van Deursch and Kwadijk, 1993); and (3) the large scale water balance model for the upper Blue Nile in Ethiopia of Conway (1997).

With the advent of increasing computing power and GIS technique, physical-based hydrologic modeling has become important in contemporary hydrology for assessing the impact of human intervention and/or possible climatic change on basin hydrology and water resources.

The use of distributed physically based (conceptual) hydrological modeling with prudent simplification is appropriate for providing a reasonable solution to large scale hydrological problems associated with planning and optimal allocation of resources. The present work concerns the development of such a model for the region of Southern Africa. The model can enable one to estimate expected monthly soil moisture, actual evapotranspiration and runoff. Such a model may be used for planning and decision support system in the region.

Generally distributed type models can be developed either on the basis of dividing the drainage basin into grid meshes of specified resolution or by identifying as many as possible recognisable upstream subcatchments in a watershed. A water balance model is developed in this study based on grid cell size of 30 by 30 min

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resolution, covering the region of Southern Africa in a view to document the seasonal regimes of soil moisture, actual evapotranspiration and runoff.

2. Methodology

2.1. Model formulation

The distributed GIS-based hydrological model (DGHM) developed in this study is based on consideration of surface and subsurface processes (Fig. 1). In the subsurface zone, soil moisture accounting technique of Thornthwaite and Mather (1957), modified as part of this study, is used in computing the water balance components like actual soil moisture (SM), evapotranspiration (AET) and runoff (TRO). The surface abstractions in terms of overland runoff and interception are accounted for by DGHM by using the SCS curve number method (SCS, 1985). The model leads to the creation of high-resolution data sets of SM, AET and TRO over the several catchments in the Southern African region, which are represented by geographically referenced grids of $0.5° \times 0.5°$ resolution.

The DGHM for the Southern African region proposed in this study is based on the combination of: (1) daily overland runoff computation using the curve number (CN) method and daily canopy evaporation or interception losses estimated from normalised vegetation indices (NDVI), in the surface processes; and (2) monthly soil moisture accounting approach in the subsurface zone.

The model handles the temporal and spatial variations of the water balance components by first solving the temporal variation of each hydrological component for a single grid cell spatially over the region. This eventually allows for hydrologic regime establishment for the region of Southern Africa.

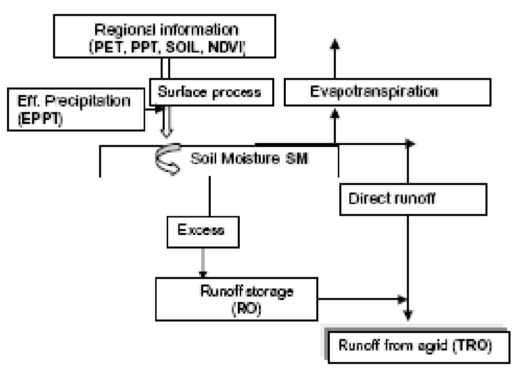

Fig. 1. Representation of water balance at a grid cell in the distributed GIS-based water balance model (DGHM).

When written in volumetric units, water balances can be given by

$$\Delta S_{M}(t) = \mathrm{PPT} - \mathrm{TRO} - \mathrm{AET} - F \tag{1}$$

where PPT is volume (depth) of precipitation, TRO is volume of runoff, AET is amount actual evapotranspiration, F is commutative infiltration. S with a subscript denotes component of storage with the subscript M for soil moisture storage. Eq. (1) is in the form, which explains that the central idea of water balance modeling is monthly accounting of soil moisture.

The water balance model given by Eq. (1) can be rearranged to estimate the total run off as follows:

$$\mathrm{TRO} = \mathrm{PPT} - (\Delta\mathrm{SM} + \mathrm{AET}) \tag{2}$$

In Eq. (2) PPT is replaced with EPPT, which is the effective precipitation, the precipitation in excess of interception loss and that flows overland, thus infiltrates to the soil.

2.2. Description and structure of the model

The model development procedure and algorithm of the water balance computation at a grid cell (using the gird runoff generation (RG) component) is schematically shown in Fig. 3.

The precipitation input is first separated into the portion that is runoff over land (DRO) and the portion that infiltrates into the soil and enters the water balance calculation called effective precipitation (EPPT). EPPT is obtained from grid precipitation (PPT) by subtracting daily evaporation as interception losses (ES) and daily overland runoff (DRO) computed by CN method of rainfall abstraction, and aggregating for month of simulation. The subsurface processes of soil moisture, actual evapotranspiration and generated runoff are presented in the subsequent sections.

2.3. Interception loss

The net precipitation that enters the soil, or infiltration, is the aggregate effect of surface processes namely, incoming precipitation, and losses through surface evaporation as interception and direct runoff. In DGHM, therefore, the daily precipitation (P) input is first separated into the following. (i) The portion that is runoff overland (Qo), (ii) the portion that infiltrates (I) and enters the soil, and (iii) the daily wet canopy surface evaporation or canopy interception losses (e_{wc}). Interception is estimated with the assumption of absence of drainage with the water balance at the canopy described by

$$\frac{\mathrm{d}C}{\mathrm{d}t} = (1-\delta)p - e_{wc} \quad 0 \leqslant C \leqslant S \tag{3}$$

where p is the precipitation rate, e_{wc} is the wet canopy evaporation rate, S is the canopy water storage capacity, C is the actual amount of water intercepted by canopy and δ is the free throughfall coefficient (the proportion of rain which falls to the ground without striking the canopy). From measurements of δ and leaf area index (LAI) of different landuses tabulated in Rutter et al. (1975), Biftu (1998) established $\delta = 0.997 - 0.139$ LAI; $R^2 = 0.997$ as a regression equation between them, and this is adopted in this study.

2.4. Modeling daily overland runoff in DGHM

Before entering the estimation of the water balance components, the daily precipitation (P) is separated into the direct runoff (Qo) and the portion that infiltrates and so enters the water balance computation as the effective rainfall.

The US Soil Conservation Service (SCS) has prepared a series of tables and nomographs by which the amount of daily overland runoff from intense precipitation can be estimated from information on slope, ground cover, soil type and antecedent precipitation. This method is usually called the SCS–CN curve method (CN formula). This method is usually recommended for daily overland runoff estimation.

Estimation of the overland runoff using the CN formula for daily overland runoff is given by

$$Qo = \frac{P - 0.2s}{P + 0.8s} \quad \text{for } P > 0.2s$$
$$Qo = 0.0 \quad \text{for } P \leqslant 0.2s \tag{4}$$

where s is a parameter related to curve number (CN) (SCS, 1985; Chow et al., 1988) as

$$s = 254\left(\frac{100}{\text{CN}} - 1\right) \tag{5}$$

The constant, 254, in Eq. (5) gives s in mm. Thus, P and Qo are also expressed in mm. Thus, the monthly volume of overland runoff is the sum of the daily overland runoff, DRO; that is, $\text{DRO} = \sum_{i=1}^{nd} Qo_i$, where, nd is the number of days in the month under consideration.

The importance of this approach in developing the DGHM is more explained in terms of the subsurface processes. It is based on the assumption that if one computes overland runoff from the total precipitation falling, then it forms the effective precipitation that goes to replenish the soil moisture.

2.5. Modeling soil moisture

Soil moisture is determined from the interaction between effective PPT and PET. During wet months (when effective PPT in excess of PET), soil moisture can increase up to a maximum of field capacity determined by soil texture and rooting depth.

$$\frac{d\,\text{SM}}{dt} = \text{EPPT} - \text{PET} \quad \text{when} \quad \text{EPPT} > \text{PET}$$
$$\text{and} \quad \text{SM} < \text{FC} \tag{6}$$

$$\frac{d\,\text{SM}}{dt} = 0 \quad \text{when} \quad \text{SM} = \text{FC} \tag{7}$$

$$\frac{d\,\text{SM}}{dt} = a\text{SM}(\text{PET} - \text{EPPT}) \quad \text{when} \quad \text{EPPT} < \text{PET} \tag{8}$$

where, FC is the soil moisture at field capacity of the soil millimetres, PPT is precipitation in mm/month; PET is potential evapotranspiration in mm/month.

During the dry periods where the EPPT < PET, the soil becomes increasingly dry, soil moisture becomes a function of potential soil loss. Thus, different authors assumed different relationship to find the soil moisture during the dry periods (Thornthwaite, 1948; Vorosmarty et al., 1989).

For a particular soil, there is a linear relationship between Log (SM) and $\sum(\text{EPPT} - \text{PPT})$ summed from the start of the dry season to the current month. Thus, to calculate the rate of change of soil moisture (ΔS) through the dry season, the soil moisture is directly estimated from the empirical relation suggested by Vorosmarty et al. (1989). To calculate $d\,\text{SM}/dt$ through Eq. (8) for intermediate field capacities, the DGHM defines a slope a to the retention function as

$$a = \ln(\text{FC})/(1.1282\text{FC})^{1.2756} \tag{9}$$

where the numerator represents soil moisture (millimeters) with no net drying. The denominator is the accumulated potential water loss or APWL ($\sum[\text{PET} - \text{PPT}]$) in mm at SM = 1 mm. With a determined, the model can calculate $d\,\text{SM}/dt$ as a function of soil dryness and update SM.

Calculations commence at the end of the wet season when it is assumed the soil is at the field capacity. Soil water stocks are then depleted during the dry season in accordance with the moisture retention function. For each wet month, soil moisture is determined by incrementing antecedent values by the excess of the available water over PET. This recharge may or may not be sufficient to bring the soil to field capacity at the end of subsequent wet season.

Analysis of the ratio PPT/PET at the various grids in Southern Africa has shown that the region cannot be represented by one homogeneous climatic zone, rather it is a combination of climate influenced by the diversified hydro-climatic conditions in the region. In this analysis, it has been observed that the long-term monthly rainfall distribution varies greatly in the region.

It is assumed that the ratio PPT/PET could be a good indicator of the seasonal distribution of monthly rainfall, and accordingly the wet season ends when the ratio PPT/PET just starts to fall below unity. In line with this, therefore, the soil moisture can be assumed to be at its field capacity. Consequently, DGHM fixes a starting month of any grid across the region according to the aforementioned criterion. The solution of the basic mass balance equation for the subsequent months can determined once the initial soil moisture state is obtained.

2.6. Actual evapotranspiration

Once the actual soil moisture is determined, the corresponding actual evapotranspiration (AET) is calculated for the month. Following the Thornthwaite and Mather (1957) approach, AET is set equal to PET in wet months, when EPPT > PET. During this time it is assumed that EPPT is in sufficient abundance to satisfy all the potential water demands of the resident vegetation. During dry season when EPPT < PET, the monthly average AET is modified downwards from its potential value as shown below.

$$\mathrm{AET} = \mathrm{PET} \quad \text{when} \quad \mathrm{EPPT} > \mathrm{PET} \tag{10}$$

$$\mathrm{AET} = \mathrm{EPPT} - \frac{\mathrm{d\,SM}}{\mathrm{d}t} \quad \text{when} \quad \mathrm{EPPT} < \mathrm{PET} \tag{11}$$

where the soil moisture drops below the wilting point, the AET is equal to the EPPT but if there is no EPPT at all time, AET becomes zero.

2.7. Total runoff generated at a grid

Most of the water does not leave the basin as soon as it becomes available as surplus. The portion that constitutes overland flow is assumed to flow out the watershed within the month it occurs but the portion that infiltrates may take a number of months to move slowly through upper layer of the soil column to emerge in the surface water courses as base flow.

The lag or delay factor depends not only the size of the basin but also on the vegetation cover and the soil type, degree of slope, characteristics of the soil rock layers, etc.

Thornthwaite suggested that 50% of the water surplus could be assumed to runoff each month from large basins with the remainder being held over and added to the surplus of the next month. This factor is set according to Thornthwaite and Mather (1957) which is equal to 0.5.

$$\mathrm{RO} = 0.5^{*}(D + (\mathrm{EPPT} - \mathrm{PET})) \quad \text{when}$$

$$\mathrm{SM} = \mathrm{FC} \text{ and } \mathrm{EPPT} > \mathrm{PET} \tag{12}$$

$$\mathrm{RO} = 0.5^{*}D \quad \text{when} \quad \mathrm{SM} < \mathrm{FC} \text{ and } \mathrm{EPPT} < \mathrm{PET} \tag{13}$$

where, RO is rainfall-driven runoff or surplus runoff (mm/month) and D is the amount of detention storage in millimeters that is assumed to leave each grid cell next month. Finally, the total runoff from the grid is calculated by adding the DRO and the RO.

$$\mathrm{TRO} = \mathrm{DRO} + \mathrm{RO} \tag{14}$$

Eq. (14) gives the runoff from each grid that is ultimately routed as discharge for any catchment in the region.

3. Creation of geo-referenced distributed input database

3.1. Geo-referencing and GIS of the study area

The study region involves the Southern African subcontinent that is encompassed between equator to 35° S latitudes and 5° E–55° E longitudes. It is divided into grids of 30 min spatial resolution representing the region by 7000 square grids (70 rows by 100 columns). Each grid point is assigned a unique ID number starting from 1 to 7000, each referenced to its latitudinal and longitudinal location. This forms the basic geo-referenced platform of the study region. Totally 3402 grids represent the land catchments of the Southern African region.

3.2. Precipitation and potential evapotranspiration input variables

Rainfall is a climatic quantity showing greater variability within a short range of spatial variation. Despite the scarcity of data in the region, distributed 1961–1990 average grid rainfall data base at 0.5°×0.5° from Hulme et al. (1996) is used in this study. The Southern African regional precipitation has been based on the thin-plate splines approach developed by Mike Hutchinson from the Australian National University.

There is no readily available potential evapotranspiration for the region of Southern Africa. However, the Southern African regional 1961–90 climatologies used in Hulme et al. (1996) exist at 0.5° resolution. The region's monthly potential evapotranspiration was computed using the Penman's method and stored at 0.5° grid resolution.

3.3. GIS-based soils and vegetation information

The FAO/UNESO soil map of Africa, available at 10×10 min resolution, is used to derive the Southern African soils data from which a 30×30 min resolution of soils database is created by pixel contraction (Eastman, 1997). The soils classification of the Africa (FAO, 1988) was based on agronomic characteristics and benefits it renders to agriculture with about 133 of such soil types. The rasterized soils map at grids of 30×30 min has been used to derive textural soil classes, which ultimately fall into six groups (Table 1).

Table 1
Distribution of textural soil classes in the Southern African region

	Sand	Sandy loam	Clay	Clay loam	Silt loam	Lithosol
No. of grids	831	320	331	1432	365	122
% coverage	24	10	9	42	11	4

To set broader rooting depths, two rooting depth categories in compliance with Vorosmarty et al. (1989) have been created. These are: (1) VEG1—this includes farmlands (or extensive crop production area), savannah with scattered trees, shrub lands, etc., and percentage forest of 50% or less of normalized difference vegetation index (NDVI). (2) VEG2—dense forest, natural vegetation cover and deciduous forest cover, and percentage of forest above 50% of mean annual NDVI have used as a criterion.

The nature of soil at a particular location and for a given vegetation cover affects the rooting depth. This has been noted in Vorosmarty et al. (1989) and is adopted. Based on the above vegetation grouping, the root depth for each soil is assigned based on the values. The SCS soil groupings for the overland flow module is assigned according to the definition given in Singh (1992) and is tabulated in Table 2.

Satellite data have been used extensively for mapping the land use and for monitoring the seasonal change of vegetation of river basins (Nemani and Running, 1989). The NDVI is commonly applied to derive the LAI from channels 1 and 2 of NOAA-AVHRR data at 1 km^2 resolution. Monthly 12 NDVI images, expressed in percentage, for 1987 are acquired from USGS web pages. Based on NDVI values the LAI for different land use groups can be estimated by empirical formulae.

3.4. Derivation of soil retention parameters

The ultimate importance of the textural reclassification of soils and vegetation is to derive retention parameters of the soils such as field capacity (FC) and wilting point (WP) values for each soil group to determine the soil moisture capacities.

Based on field measurements, Saxton et al. (1986) have developed a technique to estimate the matrix potential of different soils by using multiple regression techniques. So at a matrix potential equivalent to field capacity (33 KPa) and wilting point (1500 KPa) for a unit meter depth of soil, approximate values of FC and WP for the various soil textures have been extracted (see Table 1). Accordingly, the FC and WP values as per the rooting depth is then derived for the whole region as summarised in Table 3.

The maximum retention capacity of soils depends on the type of soil and the vegetation cover of the area. It is obtained by multiplying the UFC and UWC values by the corresponding root depth. Derived FC distribution in the SADC region used in water balance calculation is

Table 2
Rooting depth assigned for various soil textures and SCS soil groupings

Veg. group	NDVI	Assigned root depth (M) for different soil types					
		Sand	Sandy loam	Silty loam	Clay loam	Clay	Lithosol
VEG2	>50%	2.5	2.0	2.0	1.6	12	0.1
VEG1	≤50%	1.0	1.0	1.3	1.0	0.7	0.1
SCS soil group (Singh, 1992)		A	B	D	C	C	B

Table 3
Relationship linking vegetation class, soil texture, rooting depth and moisture capacities of various soil groups in Southern Africa

Veg. group	The root depth (m)					
	Sand	Sandy loam	Silt loam	Clay loam	Clay	Lithosol
GRP1	2.5	2.0	2.0	1.6	1.2	0.1
GRP2	1.0	1.0	1.3	1.0	0.7	0.1
FC and AWC of soils as % of total volume of soils/m						
% (FC)/m	14.1	20.0	27.3	35.2	48.3	27.3
% (AWC)/m	6.3	9.1	13.2	35.8	35.8	13.2
FC and AWC per root depth of the plant						
GRP1 (FC)	353	400	546	563	582	27
GRP1 (AWC)	196	218	282	243	133	14
GRP2 (FC)	141	200	355	352	339	27
GRP2 (AWC)	78	109	183	152	89	14

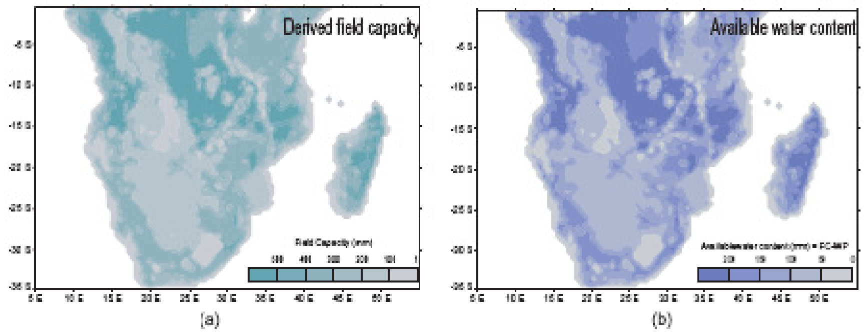

Fig. 2. Distribution of derived (a) field capacity (FC) and (b) available water content (AWC) in the SADC region used in water balance calculation.

presented in Fig. 2a. On the other hand, Fig. 2b shows the spatial variation of the derived available water content (AWC) distribution across the SADC region used in DGHM.

4. Model application and discussion of results

4.1. General principle

For a single geographically referenced grid cell, the model is run independently for the 30-year period between 1961 and 1990 to derive a regional map of hydrologic regimes. In each simulation year, the model in the subsurface zone, is run for a time loop of 12 months, by applying the PPT and PET. If a dynamic state is not achieved in SM, AET and TRO between subsequent simulations, simulation proceeds until a dynamic steady state is achieved with in 0.01% error in all of these variables. When the steady state situation is arrived, the outputs SM, EAT and TRO are maintained, and the spatial control module is invoked and computation for another grid cell continues. The model is then applied for 7000 grids that represent the study area according to their spatial identifier.

In order to establish the hydrologic regimes of the study region, the available 1961–1990 average hydro-climatological information, on monthly basis, has been used as input to the model DGHM. The seasonal variation of TRO, AET and SM for corresponding PET and PPT for a typical region in Eastern Tanzania is shown in Fig. 3a–c, respectively.

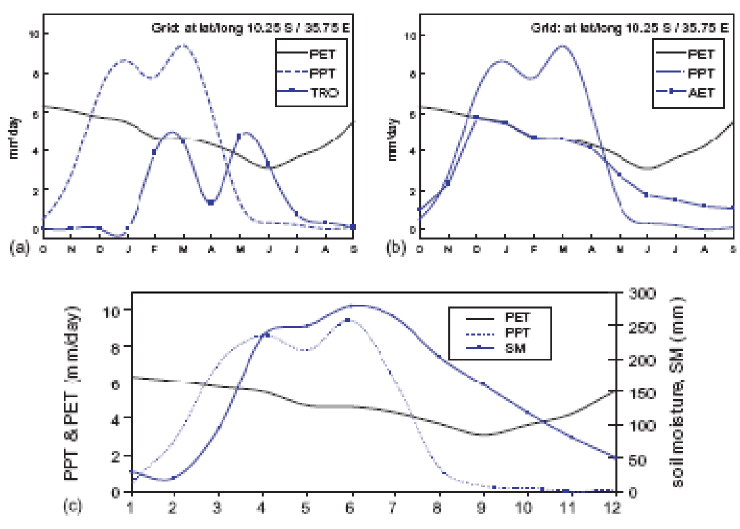

Fig. 3. Seasonal variation of precipitation and PET versus model derived (a) runoff, (b) actual evapotranspiration and (c) soil moisture for a selected grid cell the SADC region centred on Eastern Tanzania, which is dominated with soil of field capacity of 349 mm.

4.2. Soil moisture

The variation of 1961–1990 mean annual soil moisture (MASM) in Southern African region, computed by the model, is shown in Fig. 4. The MASM of the basin is estimated by the model is about 148 mm. The frequency distribution of MASM over the region portrays a significance spatial variation (Fig. 4). This is due to the fact that the absolute soil moisture depends on the water retention property of the soil, and hence on the field capacity of the soil. If the actual soil moisture is segregated by its field capacity value of the corresponding soil type, the actual regional variation can be observed clearly.

It can be observed from Fig. 4 that DGHM simulates the majority of the area Northwestern Tanzania west of the Lake Victoria extending to west of Zaire and Central Mozambique to exhibit higher annual soil moisture regimes. The highland areas in Northern and Eastern Tanzania have moderate soil moisture and most part of central and Southern Africa from Zimbabwe to southern most of Republic of South Africa are dominated by low soil moisture regimes. Generally, the map of annual average soil moisture to some extent follows the pattern of precipitation. The variation of mean annual SM with respect to the mean annual PPT is depicted in Fig. 5.

It can also be inferred from Fig. 5 that high precipitation grids experience high SM, explained by relatively high values of the ratio mean annual SM/FC. However, because PPT alone is a poor indicator of SM in absolute terms, and the variation of SM with PPT is not distinctively related, either linearly, or not otherwise. This can also be attributed because of the high variation of FC in the region shown in Fig. 4, which ranges from 27 to 563 mm that can affect the ratio of actual SM to FC. But the dependence of SM on PPT becomes more vivid if it is segregated by the field capacity.

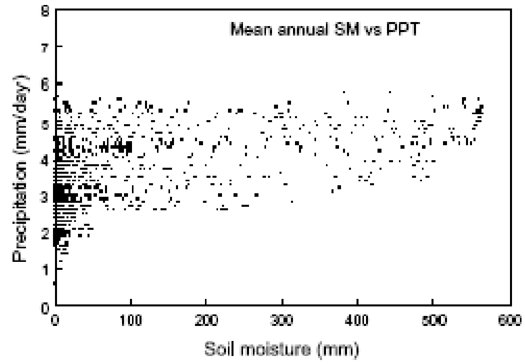

Fig. 5. The relationship between precipitation and model derived mean annual soil moisture.

4.3. Actual evapotranspiration

The variation of mean annual actual evapotranspiration in the Southern African region, simulated by the model DGHM, is shown in Fig. 6. The model prediction of the mean annual (AET) in the region reaches a maximum of 1500 mm, with mean 420 mm.

Considering the whole region, the actual mean annual AET accounts for 41% of the mean annual PET over the region. The spatial variation of the computed annual AET over the Southern African region is shown in Fig. 7. It can be seen that, PET is high in the area near the shore areas surrounded by the oceans and decreases towards hinterland. Nearly northern half of Southern African region experiences higher evaporation than the remaining southern half of the region which experiences lower evaporation.

The variation of the ratio of annual AET to PET is shown in same figure (Fig. 7). The regional variation of

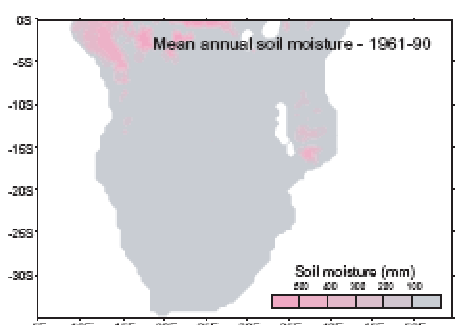

Fig. 4. Mean annual soil moisture variation for the baseline 1961–1990 over Southern Africa.

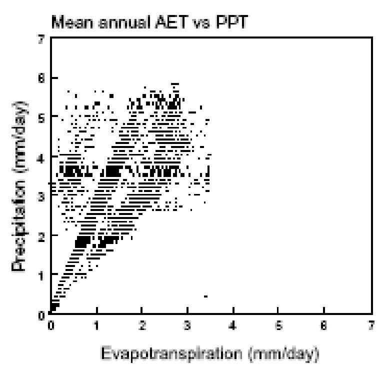

Fig. 6. The relationship between 1961 and 1990 mean annual precipitation and DGHM model derived mean annual AET over the Southern African region.