Observed and simulated changes in the water balance components over Malawi, during 1971–2000

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ABSTRACT

Estimation of the spatial and temporal characteristics of key water balance components in data scarce regions is a large challenge worldwide. This paper presents the derivation of the 30-year surface water balance components (rainfall, temperature, potential and actual evapotranspiration \(\text{ET}_p\) and \(\text{ET}_a\)) runoff. Monthly rainfall and mean temperature from 28 synoptic stations in Malawi during 1971–2000, together with soil moisture capacity extracted from the International Geosphere-Biosphere Programme Data Information Services (IGBP-DIS) Global Gridded Surfaces of Selected Soil Characteristics database at \(0.5\times0.5\) grid resolution were used as model input. Ordinary Kriging was applied to examine the spatial distribution of the components using a \(0.5\times0.5\) grid resolution. Temporal trends were investigated using the Mann–Kendall test at \(\alpha = 0.05\) significance level. The results showed: (1) an area of high rainfall, \(\text{ET}_a\) and runoff areas located in the south east and north east highlands and decreasing westwards. Temperature and \(\text{ET}_p\) were highest in the lower Shire River valley and along Lake Malawi; (2) Mann–Kendall trends suggested statistically significant positive trends in mean annual temperature and \(\text{ET}_p\) and declines in annual rainfall, \(\text{ET}_a\) and runoff, though their trends were not statistically significant. The contrasting trends \(\text{ET}_p\) and \(\text{ET}_a\) are a manifestation of the complementary relationship. The decline in rainfall coupled with temperature increase suggests that Malawi became more water-limited during 1971–2000.

1. Introduction

Water resources availability at any temporal and spatial scales is governed by complex interactions between climate and hydrological processes. Global warming induced climate change is bound to further complicate this already complex interaction, thereby affecting water resources availability through the alteration of key water balance components such as rainfall, temperature and potential and actual evapotranspiration \(\text{ET}_p\) and \(\text{ET}_a\), soil moisture and runoff (Zaninović and Gajić-Capka, 2000). Analysis of observed behavior of various water balance components for the assessment of possible influences of climatic change and variability therefore provides the basis for future climate impact assessments. However, the response of the various water balance components to climate change is not globally uniform. There are marked regional differences and this demonstrates a need to evaluate responses in different geoclimatical regions. The water balance components also respond differently to climatic changes (Wang et al., 2011).

Among the key water balance components, rainfall is perhaps the most investigated component and major regional differences are found. Globally, the Inter-Governmental Panel on Climate Change (Bates et al., 2008) reported changing precipitation patterns, intensity and extremes from 1901 to 2005, with statistically insignificant trends, although there was significant natural variability which was masking the long-term trends. Overall in southern Africa, Richard et al. (2001) found no significant changes in the summer rainfall during 1900–1999. Many large parts of southern Africa have nevertheless shown a tendency towards increased more widespread drought between 1990 and 2005 (Bates et al., 2008). More recent country based studies on rainfall temporal patterns in southern Africa include Mazvimavi (2010) who found no evidence of annual rainfall change in Zimbabwe for the period 1892 to 2000. In South Africa’s Drakensburg Mountains Region, Nel (2009) found that no statistically significant trend in inter-

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annual variability existed during the last half of the twentieth century. This was coupled with an increase in the variability of monthly rainfall. In Malawi, Ngongondo et al. (2011) analysed spatial and temporal characteristics of rainfall for the period 1961–2006 and did not detect an obvious rainfall trend pattern. Nicholson et al. (2013) provide detailed climatology for Malawi. This study builds on the study by Ngongondo et al. (2011) by analysing temporal trends of other key water balance components in addition to rainfall.

Many studies have suggested an overall statistically significant increasing temperature worldwide (Dery and Wood, 2005), rising by 0.069 °C per decade between 1900 and 2002 (Balling, 2003; Bates et al., 2008). Within southern Africa, studies of increasing temperatures include Kruger and Shongwe (2004) in South Africa, Morishima and Akasaka (2010) for the whole of Southern Africa between 1979 and 2007 and Collins (2011) between 1979 and 2010. Among the key water balance components, ETp and ETa has in many regions exhibited contrasting trends despite the expected increase of both due to global warming. Wang et al. (2011) and Jung et al. (2010) reported based on various studies a decrease in pan ET and ETp in the USA, Russia, China and New Zealand among many others. Such contrasting trends have been explained in terms of the supplementary relationship: moisture availability is the main driving factor of ET in drier and water limited areas where the ET is mainly controlled by energy availability in wetter regions. Thus, ETp should increase with positive rainfall trend in water limited areas and vice versa, whereas an increase in available energy in energy limited environments should result in an increase in both ETp and ETa (Roderick and Farquhar, 2002; Teuling et al., 2009; Matsoukas et al., 2011).

Global runoff trends are also quite unclear with contrasting patterns between regions and sometimes model dependant further constrained by good quality river discharge data availability (Alkama et al., 2011; Jung and Chang, 2011). Some studies have however found statistically significant links of trends in runoff, rainfall, and temperature (Bates et al., 2008). Some regionally consistent patterns have been established with runoff increases high latitude areas and many parts of the USA and decreases in Southern Europe, West Africa and parts of South America (Bates et al., 2008). Labat et al. (2004) report of a significant increase in the twentieth century global runoff with a decrease in runoff over Africa attributed to rainfall decrease.

Although the catchment scale water balance provides the ideal basis for water resources assessments and associated studies of changes in key water balance components, data availability constraints have resulted in the development and application of generalized assessment approaches. Such methods include the Thornthwaite Water Balance and the Palmer Drought Severity Index Methods. Kerkides et al. (1996) provided an estimate of the water balance of Greece based on 31 stations for the period 1960–1987. The study replaced the Thornthwaite equation in Thornthwaite and Matther’s original method by (ETa) values, estimated using the Penman equation and used more appropriate water capacities of the root zone, and suggested that records of soil moisture deficits can be very useful for water resources management. Mavromatis and Stathis (2011) built on the study by Kerkides et al. (1996) and analysed the most recent trends in point based water balance components derived from Palmer’s Aridity Index at 17 stations in Greece for the period 1960–2006. The study found downward trends in precipitation (P) and runoff (RO) in spring and summer, the latter coupled with increased ETp. Pandžić et al. (2009) applied the Palmer methods in the analysis of water balance trends in Croatian Lowlands during various periods within 1862 and 2000. They found long-term positive trends in air temperature, ETp, and ETa, negative trends in runoff and a cyclic rainfall pattern. Over Africa, Nicholson et al. (1997) investigated the surface water balance over Africa based on approximately 1400 rainfall stations during 1925–1990. They applied a revised version of a model called Evapo-climatology of the surface water balance by Nicholson et al. (1996). The Evapo-climatology model computed point based monthly water balance components (ETa, runoff and soil moisture) at each of the stations. The values of the station based water balance components were then spatially interpolated over Africa to provide maps of mean precipitation, ETp and runoff at a grid resolution of 0.5° × 0.5°. The study found strong interdecadal rainfall variability, although the temporal trends of the water balance components were not investigated. Apart from the study on rainfall trends and spatial characteristics by Ngongondo et al. (2011) which found a predominance of negative trends in Malawi, no integrated study investigating temporal characteristics of key water balance components in Malawi is documented in the literature. This is a data scarce region which poses considerable challenges to conventional hydrological modeling approaches thereby necessitating the application of less data intensive, but reasonable approaches in water resources assessments.

The main aim of this study is to investigate the spatial and temporal characteristics of key water balance components (rainfall, temperature, ETp, ETa and runoff) in Malawi based on data from 28 stations for the period 1971–2000. Specifically, we (i) derived water balance components using a simple monthly water balance model from point observations of rainfall and temperature; (ii) analysed spatial patterns of the long term annual means of the water balance components; and (iii) analysed temporal trends of the annual water balance components.

2. Description of the study area and data

Malawi is located in southern Africa between latitudes 9.5–17°S and longitudes 32–36°E (Fig. 1). It has a total area of 118,484 km², of which 94,080 km² is land and 24,404 km² is occupied by lakes and rivers. Most of Malawi is part of the Zambezi River basin except the Lake Chilwa basin, which is located to the southeast of the country. The topography is dominated by the Great Rift Valley extending from the North to the South of the country, which contains Lake Malawi, and the landscape around the valley consists of large plateaux at an elevation of around 800–1200 m a.s.l., with peaks as high as 3000 m a.s.l. Malawi experiences a mild tropical climate with an austral summer rainy season between November and April and a dry season between May and October. Rainfall depends on the position of the Inter-tropical Convergence Zone (ITCZ) and varies in its timing and intensity from year to year. Countrypwide rainfall varies from 725 mm in the low lying rift valley to 2500 mm in the highlands. Temperature is also controlled by the varying topography and range from 22 °C to 27 °C in the summer months. In the dry season (winter months) between May and August, daily temperatures drop to around 18 °C whereas night-time temperatures drop to near 5 °C (Jury and Mwafulirwa, 2002). According to Mandeville and Batchelor (1990), average annual runoff (in percentage of average annual rainfall) varies between 4% in the drier parts of plateau areas and 54% in the highlands where most streams are perennial.

2.1. Data availability

Daily temperature, from which monthly values were computed, and monthly rainfall data from 28 weather observation stations in Malawi covering the common period 1971–2000, were sourced from the Malawi Department of Climate Change and Meteorological Services. The chosen period had the longest available station series for all the required rainfall and temperature input data that
fairly covered Malawi. Table 1 lists the basic information of the stations including their location, percentage of missing data and elevation, and the geographic distribution of the stations is shown in Fig. 1.

The rainfall data were subjected to a range of quality control tests in the study by Ngongondo et al. (2011). The quality controlled data from that study were hence adopted. The daily temperature data were subjected to similar quality control procedures (using the

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Table 1: Stations list including their location (latitude and longitude) and altitude.

<table>
<thead>
<tr>
<th>Serial</th>
<th>Station</th>
<th>Lat (°S)</th>
<th>Long (°E)</th>
<th>Elevation (m a.s.l)</th>
<th>Serial</th>
<th>Station</th>
<th>Lat (°S)</th>
<th>Long (°E)</th>
<th>Elevation (m a.s.l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Alumenda</td>
<td>−16.3</td>
<td>34.94</td>
<td>80</td>
<td>15</td>
<td>Makoka</td>
<td>−15.52</td>
<td>35.22</td>
<td>1029</td>
</tr>
<tr>
<td>2</td>
<td>Balaka</td>
<td>−14.92</td>
<td>34.87</td>
<td>625</td>
<td>16</td>
<td>Mangochi</td>
<td>−14.43</td>
<td>35.25</td>
<td>482</td>
</tr>
<tr>
<td>3</td>
<td>Bolero</td>
<td>−11.02</td>
<td>33.78</td>
<td>1100</td>
<td>17</td>
<td>Mimosa</td>
<td>−16.08</td>
<td>35.58</td>
<td>652</td>
</tr>
<tr>
<td>4</td>
<td>Bvumbwe</td>
<td>−15.92</td>
<td>35.07</td>
<td>1146</td>
<td>18</td>
<td>Mkanda</td>
<td>−13.52</td>
<td>32.95</td>
<td>1219</td>
</tr>
<tr>
<td>5</td>
<td>Chanco</td>
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<td>35.35</td>
<td>886</td>
<td>19</td>
<td>Monkey bay</td>
<td>−14.04</td>
<td>34.92</td>
<td>482</td>
</tr>
<tr>
<td>6</td>
<td>Chichiri</td>
<td>−15.8</td>
<td>35.05</td>
<td>1132</td>
<td>20</td>
<td>Mzimba</td>
<td>−11.88</td>
<td>33.62</td>
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</tr>
<tr>
<td>7</td>
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<td>34.97</td>
<td>767</td>
<td>21</td>
<td>Mzuzu</td>
<td>−11.43</td>
<td>34.02</td>
<td>1254</td>
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<tr>
<td>8</td>
<td>Chitedze</td>
<td>−13.97</td>
<td>33.63</td>
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<td>Nchalo</td>
<td>−16.27</td>
<td>34.92</td>
<td>52</td>
</tr>
<tr>
<td>9</td>
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<td>−9.7</td>
<td>33.27</td>
<td>1285</td>
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<td>Ngabu</td>
<td>−16.5</td>
<td>34.95</td>
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</tr>
<tr>
<td>10</td>
<td>Dedza</td>
<td>−14.32</td>
<td>34.27</td>
<td>1632</td>
<td>24</td>
<td>Nhatalbay</td>
<td>−11.6</td>
<td>34.3</td>
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</tr>
<tr>
<td>11</td>
<td>Karonga</td>
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<td>33.95</td>
<td>1230</td>
<td>25</td>
<td>Nkhotakota</td>
<td>−12.92</td>
<td>34.28</td>
<td>500</td>
</tr>
<tr>
<td>12</td>
<td>Kasungu</td>
<td>−13.03</td>
<td>33.46</td>
<td>529</td>
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<td>Ntaja</td>
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<td>35.53</td>
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<tr>
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<td>Kamuzu Airp</td>
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<td>33.78</td>
<td>1036</td>
<td>27</td>
<td>Salima</td>
<td>−13.73</td>
<td>34.6</td>
<td>512</td>
</tr>
<tr>
<td>14</td>
<td>Makhanga</td>
<td>−16.52</td>
<td>35.15</td>
<td>76</td>
<td>28</td>
<td>Thyolo</td>
<td>−16.15</td>
<td>35.22</td>
<td>820</td>
</tr>
</tbody>
</table>
Anclim software) (Stépánek, 2007). The software allows the filling of gaps in the series using absolute testing (single station) and relative testing (using nearby reference stations) procedures. The choice of nearby stations was based on proximity and correlation between the stations.

3. Methods

This section presents the methods applied starting with the Thornthwaite Monthly Water Balance Model. The procedure interpolates in space based on point based measurements similar to other studies using the Palmer procedure (Palmer, 1965) in point based water balance assessments: e.g. Nicholson et al. (1997) over Africa; Zaninović and Gajić-Capka (2000) in Croatian Lowlands; and Mavromatis and Stathis (2011) in Greece. This is followed by an introduction to the spatial and temporal techniques that were used to analyse the various water balance components.

3.1. Thornthwaite monthly water balance model

The water balance components were simulated using the Monthly Water Balance Model by the U.S. Geological Survey (McCabe and Markstrom, 2007). The model takes point based inputs of monthly rainfall (\(P_{\text{total}}\), mm), monthly mean temperature (°C), latitude (°S or °N of the equator) and soil holding capacity (mm). The model then simulates point based potential evapotranspiration (\(ET_p\) (mm), actual evapotranspiration (\(ET_a\) (mm)), soil moisture storage (ST, mm) and soil moisture storage withdrawal (STW, mm). \(ET_p\) is calculated using the Harmon equation:

\[
ET_p = \frac{13 \times d \times D^2 \times W_t}{100}
\]

where \(ET_p\) is \(ET_p\) (mm per month), \(d\) is the number of days in a month, \(D\) is the mean monthly hours of daylight in units of 12 h and

\[
W_t = \frac{4.95 \times e^{0.062 \times T}}{100}
\]

is a saturated water vapour density term, in grams per cubic meter, at temperature \(T\) in (°C). \(ET_a\) is then calculated in two ways:

(i) If \(P_{\text{total}} < ET_p\), then \(ET_a = P_{\text{total}} + \text{STW}\), where STW is the amount of soil moisture that can be withdrawn from storage in the soil, given by:

\[
\text{STW} = \text{ST}_{i-1} - \left[ \left| P_{\text{total}} - ET_p \right| \times \left( \frac{\text{ST}_{i-1}}{\text{STC}} \right) \right]
\]

(ii) If \(P_{\text{total}} > ET_p\), then \(ET_a = ET_p\) and \(ST\) increases.

where \(P_{\text{total}}\) is the monthly rainfall (mm), \(ET_p\) is the monthly potential evapotranspiration (mm), \(\text{ST}_{i-1}\) is the soil moisture storage for the previous month (mm) and \(\text{STC}\) is the soil-moisture storage capacity (mm). Runoff is only generated when \(ST > STC\). In this study, point values of \(STC\) for Malawi were extracted from a 0–1 m soil layer from the IGBP-DIS Global Grid Surfaces of Selected Soil Characteristics database (Global Soil Data Task Group, 2000). The IGBP-DIS gridded soil data is provided at 5 x 5 arc minutes (Gao et al., 2007). Model parameters that have to be determined in each case are the runoff factor (normally set to default 0.5), direct runoff factor, soil-moisture storage capacity, and the rain temperature threshold. In addition, the latitude of the location must be known.

Model selection is many cases dependent on many factors primary of which are the purpose of the study and data availability (Gleick, 1986; Ng and Marsalek, 1992; Jiang et al., 2007; Xu, 1999). For assessing water resources management on a regional scale, monthly rainfall-runoff water balance models have been found particularly useful for identifying hydrologic consequences of changes in temperature, precipitation and other water balance components (Mimiko et al., 1991; Xu and Singh, 1998; Jiang et al., 2007). The monthly water balance model was therefore chosen in this study owing to its lower data demands as well as its suitability for assessing regional scale water resources. As highlighted by Xu and Singh (2005), it cannot be guaranteed that monthly water balance models can yield true results, but nevertheless they can be used for comparison purposes and as a starting point in water resources assessments. Such comparisons are vital especially in data scarce regions like Malawi where water resources assessments can be quiet challenging due to unavailability or poor quality of river discharge and meteorological data.

3.2. Spatial and temporal analysis

The long term annual mean of each of the water balance components under consideration was obtained from the simple arithmetic average of the respective temporal time series. The spatial distribution of the long term annual means of each of these components was obtained by interpolation using ordinary Kriging (e.g. Cong et al., 2010). Ordinary Kriging has been widely used in the spatial interpolation of climatic and hydrological variables with considerable success at daily, monthly, and annual time scales (e.g. Xu et al., 2006; Zhang et al., 2007; Cong et al., 2010). A 5 km by 5 km grid resolution across Malawi was used for spatial interpolation owing to high rainfall variability over relatively low spatial scales in the tropics as discussed by Ngongondo et al. (2011).

The temporal trends of the water balance components were investigated using the non-parametric Mann–Kendall test statistic (Mann, 1945; Kendall, 1975) recommended by the World Meteorological Organization (WMO, 1988). The slopes of the trends were quantified using linear regression. The linear regression slopes were also interpolated on a map of Malawi using ordinary Kriging to show its spatial variation pattern.

4. Results and discussion

4.1. Spatial distribution of the water balance components

The averages of the water balance components over Malawi for the period 1971–2000 are shown in Table 2. Fig. 2 shows the typical monthly distribution of the water balance components at selected

<table>
<thead>
<tr>
<th>Key: Runoff</th>
<th>AET = Annual Actual Evapotranspiration; PET = Annual Potential Evapotranspiration; AET = Annual Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated in two ways:</td>
<td>(ET_p)</td>
</tr>
<tr>
<td>(mm/year)</td>
<td>(°C)</td>
</tr>
<tr>
<td>Mean</td>
<td>1021.6</td>
</tr>
<tr>
<td>Std Dev</td>
<td>270.3</td>
</tr>
<tr>
<td>CV (%)</td>
<td>26.5</td>
</tr>
</tbody>
</table>
Fig. 2. Water balance components at selected stations over Malawi.

Fig. 3. Spatial distributions of average annual (a) Rainfall (mm), (b) Temperature (°C), (c) $ET_p$ (mm), (d) $ET_a$ (mm) and (e) Runoff (mm) during 1971–2000.
stations across Malawi, whereas Fig. 3 (a)–(e) shows the spatial distributions of the long-term mean of each of the components.

The countrywide annual mean rainfall was 1021.6 mm with a mean coefficient of variation of 26.5% during 1971–2000 (Table 2). The highest rainfall areas are located to the south east of the country and part of the Lake Malawi shore area with mean annual rainfall above 1400 mm (Fig. 3a). The area along the Shire River and the Lilongwe–Mzimba plains had the lowest average rainfall with less than 1000 mm per year. This finding for 1971–2000 does not differ from the results by Ngongondo et al. (2011) for the longer period 1961–2006. This also agrees in general with findings by Nicholson et al. (1997) in the water balance assessment over Africa during 1950–1989. However, this study also found a slightly higher mean annual rainfall of 1115 mm for Malawi for the period 1971–1978, which is in general agreement with the study by Mandeville and Batchelor (1990) who estimated the mean rainfall of 1190 mm during the same period. According to Nicholson (2000), the 1970s were marked by abnormally high rainfall throughout most of the southern Hemisphere-Africa.

Mean annual temperature for Malawi during 1971–2000 was 22.6 °C ranging from above 28 °C in the Lower Shire area in the extreme south to less than 22 °C in the highlands to the south east, parts of the central highlands and most of the north (Fig 3b). The spatial distribution of temperature is also reflected in the values for ET_p (Fig 3c), which has a countrywide annual mean of 1065.5 mm.

The ET_a with annual mean of 718.6 mm, has a similar spatial distribution as rainfall varying from more than 850 mm in the south east and parts of the lakeshore, to slightly less than 700 mm in parts of the upper Shire area extending to the western part of Malawi (Fig 3d). This study shows some reduction as compared to Nicholson et al. (1997) who, during 1950–1989, found a mean annual ET_a of approximately 1000 mm to the north and south east of the country, to between 750 mm and 1000 mm for the rest of the country. We can only speculate that this difference is attributable to different number and distributions of stations used in the two studies as well temporal periods of analysis.

The mean annual average runoff for Malawi was 303 mm, ranging from more than 600 mm in the highlands to less than 100 mm in areas located to the extreme south and western parts of the central and northern region. The runoff pattern slightly differs with that of Nicholson et al. (1997) during 1950 and 1989 who found that the runoff varied from about 100 mm in the south and western part of the country, to approximately 200 mm in the highlands. The differences in the runoff can also be possibly due to the stations used in the two studies, with this study having a larger station density over Malawi.

4.2. Temporal trends in water balance components

The temporal pattern and linear trends (dashed line) of standardized anomalies in annual rainfall, temperature, ET_p, ET_a and runoff (averaged over the period 1971–2000) are shown in Fig. 4 (a)–(e). A slight decrease in rainfall, ET_a and runoff and slight increases in temperature and ET_p can be seen. Table 3 shows the Mann–Kendal (MK) trends direction for the water balance components at each of the 28 stations and their distributions in terms of directions are summarized in Table 4. We observed the
following temporal trends for each of the water balance components:

4.2.1. Annual rainfall

Annual rainfall MK trends at 19 of the 28 stations were negative, though only one station had a statistically significant negative trend (Tables 3 and 4 and Fig. 5a). MK trend for the countrywide mean rainfall was −0.61 and the linear regression trend suggests that the mean annual rainfall over Malawi decreased at the rate of −3.24 mm/year. The spatial distributions of trends in rainfall (Fig. 6a) suggest a general north to south and east to west decrease in the rate of change of rainfall in most parts of the south, central and to the extreme north. This suggests that there has been a slight decrease in rainfall in the high rainfall areas to the south eastern highlands and in the highlands along Lake Malawi.

Declining rainfall trends pattern over southern Africa has been documented by other studies. Morishima and Akasaka (2010) reported a decrease in annual rainfall over most of the African continent from the equator to 20°S during 1978–2007. In Malawi, Ngongondo et al. (2011) did not find any discernible upward or downward trends in rainfall variables including annual, seasonal, and monthly rainfall during 1961–2006. Hoerling et al. (2006) reported a downward trend over Africa during the 1950s to 1999, with a 10% decrease over southern Africa during the period. The study by Hoerling et al. (2006) observed a strong correlation between the rainfall declines over Africa and natural variations in Sea Surface Temperatures (SSTs) throughout the tropics. Over Southern Africa, the Indian Ocean SST’s warming trend was found to exert a drying influence in the region’s rainfall cycle.

4.2.2. Mean annual temperature

The MK trends show that mean annual temperature in Malawi during 1971–2000 increased significantly (Tables 3 and 4 and Fig. 5b). For the countrywide areal mean temperature, the MK trend was +3.89, showing a statistically significant increase. Only two stations (Dedza in the centre and Ngabu in the South) had positive MK trends that were not statistically significant. Further, only two stations (Kamuzu Airport and Mkanda in the centre) had negative temperature trends, however, statistically not significant. The linear regression slopes of the trends suggest a countrywide average mean temperature increase of +0.03 °C/year or a total of about +0.90 °C during 1971–2000. The highest average increase of +0.11 °C/year was centred around Balaka station on the boundary between the central and southern regions (Fig. 6b), extending to the southern shores of Lake Malawi (Mangochi and Monkey Bay area). On the other hand, a zone without trend extended from Kamuzu Airport to the west of the central region. During this period, the Northern part of Malawi experienced temperature increases averaging +0.032 °C/year. The predominance of statistically significant increases in mean annual air temperatures are broadly consistent with previous findings in Malawi (e.g. McSweeney et al., 2008 who found a temperature increase of +0.9 °C between 1960 and 2006) and other findings within southern Africa: Kruger and Shongwe (2004) for example, found positive trends in annual average temperature series of 24 stations in South Africa during 1960–2003, with significant trends at 18 of the stations. More recently, Collins (2011) attributed the statistically significant increases in air temperature over most of Africa during 1979 and 2010 to natural climatic variability with the possible influence of anthropogenic activities. The decrease in rainfall coupled with an increase in temperature agrees with Kenabatho et al. (2012) who also established statistically significant correlations between rainfall decrease and temperature increase in Botswana from 1965 to 2008.

4.2.3. Annual potential and actual evapotranspiration (ETp and ETa)

The MK trends of ETp suggest an increasing trend at all stations (Tables 3 and 4 and Fig 5c). Countrywide, the MK trend for ETp was +2.31, which was statistically significant. The linear regression suggests that average countrywide ETp increased at the rate of +1.13 mm/year. The increasing ETp trends were statistically significant at 21 stations, while 7 stations, four in the centre and three in the south, did not show statistically increasing trends. The spatial distributions of the ETp trends followed the pattern of temperature trends countrywide (Fig 6c). The ETp increased on average at +0.22 mm/year with a maximum centred at Balaka (+0.98 mm/year) and the lowest increase was 0.01 to the west of the central region. In the north, an increase of +0.2 mm/year was found. This is to be expected since the Harmon’s equation used in the PET computation by the Thornthwaite’s monthly water balance model, is predominantly dependent on the temperature as its input.

Contrary to the pattern of trends in the ETp, the country was dominated by a decrease in the ETa during 1971–2000, with the
mean annual ETa over Malawi having a negative MK trend of $-1.22$ (only statistically significant at two stations). This means that the ETa declined at the rate of $-1.45$ mm/year. There was a predominance of negative trends at 22 of the 28 stations (Tables 3 and 4 and Fig 5d), with two stations, Chitipa in the extreme north and Chancellor College in the southern highlands, showing statistically significant declines of ETa. The linear regression trends (Fig 6d) suggest ETa decreased at an average of $-0.11$ year during 1971–2000.

ETa is mainly governed by changes in atmospheric demand as a result of changing radiation and changes in vapour-pressure deficit which is temperature dependent when soil moisture supply is not limited. In the case of soils becoming too dry, ETa is then restricted by soil moisture supply (Jung et al., 2010). A decline in soil moisture will therefore result in a decline in ETa in cases of limited soil moisture supply, even if the atmospheric evaporative demand (ETa) increases. The contrasting trends of ETp and ETa over Malawi can be explained by the complementary relationship (Bouchet, 1963), whose drivers of change have also been brought forward at regional scales (Hobbins et al., 2004; Teuling et al., 2009; Jung et al., 2010). The complementary relationship derives as:

$$ET_a = 2ET_w - ET_p$$

where ETw is the wet environment ET. Two sets of ET environments have been proposed: “water limited” environments where water

Fig. 5. Mann–Kendall trends for annual water balance components over Malawi during 1971–2000. (a) Rainfall. (b) Temperature. (c) ETp (d) ETa. Upward triangles represent positive trends; downward triangles represent negative trends; dots represent no trend; shaded triangles represent significant trends at $\alpha = 0.05$.

Fig. 6. Spatial distribution of linear regression trends for annual water balance components over Malawi during 1971–2000. (a) Rainfall (mm/year). (b) Temperature (°C/year). (c) ETp (mm/year). (d) ETa (mm/year).
availability primarily controls the ET rates (mostly arid and semi areas); and “energy limited” environments, where water availability is sufficient at all times such available energy primarily controls the ET. When moisture is readily available, the ETp and ETa both assumes values of the ETw (Hobbins et al., 2004; Yang et al., 2007). When soil moisture fall below field capacity, ETw would be less than the ETw and part of the energy will not be used for ET, and the excess energy instead heat up the air thus increasing ETp. To demonstrate the complimentary relationship, annual ETa and ETp series at each of the 28 stations used in this study have been plotted against their annual rainfall series in Fig. 7 (after Hobbins et al., 2004) as a generalisation and not necessarily to explain what happens at the event scale (e.g. daily scale). In Fig. 7, the effects of changes in the radiative budget (Qn) and the advective budget (Ea) on actual ETp and ETa over Malawi are shown by ±Qn and ±Ea respectively with the arrows showing the direction of the trends. When the radiative budget increases (or decreases) (+Qn), both ETp and ETa increase (or decrease). When the advective budget increases, ETa decreases and this is compensated by an equal increase in ETp. Conversely, a decrease in the advective budget results in an increase in ETa coupled with an equal decrease in ETp. For our study in Malawi, the trends in ETa follow the decreasing trends in rainfall countrywide. Such trends in ETa are typical of water limited environments where the trends are predominantly driven by moisture supply and not the evaporative demand (Hobbins et al., 2008). On the other hand, the trends in ETp follow the temperature trends, both which suggest an increase during 1971–2000.

4.2.4. Annual runoff

Annual runoff exhibited a spatial pattern of slightly negative trends similar to that of rainfall (Tables 3 and 4 and Fig. 5e). Nevertheless, the mean runoff over Malawi had a non-significant negative MK trend of −0.58. The linear regression slopes showed that the runoff declined at the rate of −1.81 mm/year. Overall, Tables 3 and 4 show the predominance of negative trends at 17 stations, albeit only one station, Karonga station in the north, showing statistically significant decline. Countrywide an average decline of −0.09 mm/year was found. The largest decline was to the north of the country and reached a maximum of about −1.1 mm/year at Karonga Station (Fig. 6e).

5. Conclusions

This study has analysed spatial patterns and temporal trends in the annual water balance components of 28 stations over Malawi during 1971–2000. The study applied the Monthly Water Balance Model using point based observations of monthly rainfall and mean air temperature from the stations to simulate ETp and ETa and runoff. The results found the highest rainfall in the south east of the country, just as in Ngongondo et al. (2011) for the period 1961–2006. Highest temperature and ETp rates were found to the south in the Lower Shire valley area. However, ETa and annual runoff were the highest in the high rainfall areas identified. During 1971–2000, the country experienced general declines in rainfall, ETa and annual runoff, although the results were not statistically significant (α = 0.05). Temperature and ETp on the other hand, showed a statistically significant increase. The contrasting trends in ETp and ETp suggest that the declining rainfall over Malawi has resulted in a decrease in ETa due to moisture limitations. The decrease in ETa is therefore a response the increase in the ETp as a result of changes in the radiative (Qn) and the advective Ea budgets following the complimentary relationship. These results suggest that Malawi became more “water limited” as a result of the reduction in rainfall during 1971–2001, whose effects are also evident in the annual ETa and annual runoff trends.

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