Changing hydroclimatic and discharge patterns in the northern Limpopo Basin, Zimbabwe

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Abstract

Changing regional and global trends in climate and discharge, such as global warming-related declines in annual rainfall in south-eastern Africa, are likely to have a strong influence on water resource availability, and to increase livelihood risk. It is therefore important to characterise such trends. Information can be obtained by examining and comparing the rainfall and runoff records at different locations within a basin. In this study, trends in various parameters of temperature (4 stations), rainfall (10 stations) and discharge (16 stations) from the northern part of the Limpopo Basin, Zimbabwe, were statistically analysed, using the Spearman rank test, the Mann-Kendall test and the Pettitt test. It was determined that rainfall and discharge in the study area have undergone a notable decline since 1980, both in terms of total annual water resources (declines in annual rainfall, annual unit runoff) and in terms of the temporal availability of water (declines in number of rainy days, increases in dry spells, increases in days without flow). Annual rainfall is negatively correlated to an index of the El Niño – Southern Oscillation phenomenon. The main areas of rising risk are an increasing number of dry spells, which is likely to decrease crop yields, and an increasing probability of annual discharge below the long-term average, which could limit blue-water availability. As rainfall continues to decline, it is likely that a multiplier effect will be felt on discharge. Increasing food shortages are a likely consequence of the impact of this declining water resource availability on rain-fed and irrigated agriculture. Declining water resource availability will also further stress urban water supplies, notably those of Zimbabwe's second-largest city of Bulawayo, which depends to a large extent from these water resources and already experiences chronic water shortages.

Keywords: climate variability, climate change, discharge analysis, Pettitt test, rainfall analysis, water resources, Limpopo Basin, Zimbabwe, Southern Africa

Introduction

Rainfall in south-eastern Africa is temporally and spatially intermittent (Unganai and Mason, 2002). Annual rainfall for some sites can vary by up to 1 000 mm·a^{-1} from year to year (Twomlow and Bruneau, 2000). A drought year may record less than 250 mm·a^{-1}, such as the 2004-2005 season in the Limpopo Basin (Love et al., 2006). Rainfall variability in south-eastern Africa is strongly influenced by the coupled ocean-atmosphere El Niño – Southern Oscillation phenomenon (ENSO) (Trenberth et al., 2007). Positive ENSO anomalies generally result in reduced rainfall in the region and are becoming more common (Makarau and Jury, 1998; Alemaw and Chaoka, 2006). Furthermore, there has been a general decline in rainfall in Southern Africa since 1961 (New et al., 2006), with the period 1986-1995 being the driest decade of the 20th century (Trenberth et al., 2007). General circulation models developed with the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC SRES) scenarios suggest that annual rainfall in south-eastern Africa will decline further under the impact of global warming (Christensen et al., 2007). This is expected to be between 10% and 20% below the 19001970 averages by 2050 (Milly et al., 2008) or by up to 10% below the 1980-1999 averages by 2099 (Christensen et al., 2007).

Declines in rainfall, as discussed above, may translate into more than proportional declines in discharge due to non-linear processes, including, for example, interception thresholds. By the years 2041-2060 in south-eastern Africa, runoff is expected to decline by between 10% and 40% compared to 1900-1970 averages (Milly et al., 2005: Fig. 4a).

These changing regional and global trends in climate and discharge are likely to have a strong influence on water resource availability, and increase livelihood risk. It has been shown that household food security in southern Africa is highly vulnerable to climate stress (Archer et al., 2007). Already in much of southern Africa there is a precarious balance between available water resources and water demand as a result of generally low conversion of rainfall to runoff and potential evaporation exceeding rainfall (e.g. Mazvimavi, 2004). Frequently, the water yield from the developed surface water resource falls short of the demand, deficits being more evident during the frequent droughts (e.g. Nyabeze, 2004). Furthermore, some catchments, especially within the Limpopo Basin, are already over-committed (Kabel, 1984; Basson and Rossouw, 2003), leading to water stress: a high ratio of water withdrawal or water use to discharge (Vörösmarty et al., 2000). Changes of this nature constitute a major challenge to water resources management (Milly et al., 2008).

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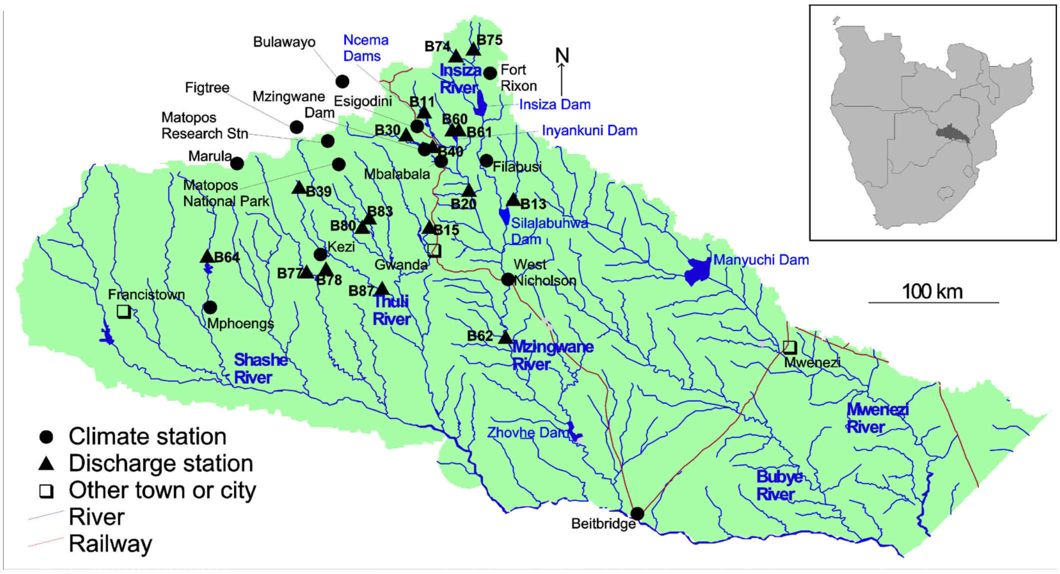

Figure 1
Map of the study area showing climate and discharge stations used. Inset: location of study area within southern Africa (shaded)

Information on water resource availability, past and present trends and future predictions, can be obtained by examining and comparing the rainfall and runoff records at different locations within a basin. Multi-decadal temporal trends of discharge, rainfall and temperature can be analysed to assess risk to strategic water resource systems (e.g. Hundecha and Bárdossy, 2005; Chen et al., 2007) or to attribute causes of change (e.g. Anderson et al., 2001).

In this study, temperature, rainfall and discharge trends from a series of locations in the northern part of the Limpopo Basin, Zimbabwe, are analysed, in order to determine the:

- Stationarity of the time series and any observed changes on water resource availability
- Causes of any changes observed
- Relationships between rainfall and discharge in the study area and causes thereof
- Implications of any changes

Methods

Study area

The study area is the drainage basins of the Shashe (18 991 km^2) and Mzingwane Rivers (15 695 km^2), in the northern Limpopo Basin, and selected stations are within Zimbabwe (Fig. 1). The 2 sub-basins contribute 12.3% and 9.3% of the mean annual runoff of the transboundary Limpopo basin, respectively. This makes them the third- and fourth-largest contributors to the Limpopo basin, after the Olifants (32.7%, 68 450 km^2 area) and Luvuhu (13.1%, 4 826 km^2 area) sub-basins (Görgens and Boroto, 1997).

Occurrence of rainfall in Zimbabwe is mainly connected to the Inter Tropical Convergence Zone (ITCZ). The movement of the ITCZ from the equator marks the start of the rainy season in the southern hemisphere. In a normal year, it fluctuates half-way between Tanzania and Zimbabwe but never moves beyond the Limpopo River in the south. The ITCZ moves with the sun, southwards at the start of summer (October/November) and northwards in late summer (March/April) (Twomlow et al., 2006). Because of this, the wet season in the southern parts of Zimbabwe (including the northern part of the Limpopo Basin, also known as the Mzingwane Catchment) starts later and ends sooner than in the northern areas. Furthermore, the northern winds in the convergence are moister than the southern winds, leading to less frequent rainfall in the southern areas than the north, for a given air moisture level. Rainfall in southern Zimbabwe thus occurs over a limited period of time, and often a large portion of the annual rainfall can fall in a small number of events (Twomlow and Bruneau, 2000; Unganai and Mason, 2002; De Groen and Savenije, 2006). These short, intense rain spells, if they occur at critical stages during crop growth, can exercise a strong control on crop yields (Twomlow et al., 2006). Within the study area, annual rainfall generally decreases from the North to the South: from around 630 mm·a^{-1} at Esigodini, to 560 mm·a^{-1} at Filabusi, to 360 mm·a^{-1} at Beitbridge (see Table 2).

Data series

A statistical analysis was carried out of daily temperature, rainfall and runoff data from several stations (see Fig. 1). Stations with a minimum of 30 years continuous data were selected. Data were organised into the Southern African hydrological year of October to September.

All selected discharge stations were upstream of major dams and with limited upstream water users (see table 3 for water use upstream of the discharge stations and Fig. 1 for the locations of the discharge stations in relation to major dams) and did not require naturalisation.

Table 1
Selected information on major dams in the northern Limpopo Basin, operated by the Government of Zimbabwe. For locations, see Fig. 1.

Dam	Year of construction	Full storage capacity (10^6·m^3)
Mzingwane	1962	42
Lower Ncema	1964	17
Inyankuni	1963	75
Silalabuhwa	1966	23
Upper Ncema	1973	45
Insiza (Mayfair)	1973	173
Manyuchi	1988	303
Zhovhe	1996	136
Glassblock	planned	14

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Table 2 Data sets from the climate stations used in this study, showing data availability and general rainfall characteristics. All data were computed from records in the national database of the Department of Meteorological Services.						
Station	Mean annual rainfall (mm/a)	Mean rainy days (no. d/a $p > 0.5$ mm/d)	Rainfall data (hydrological years ending)		Temperature data (hydrological years ending)	
			Data period	Missing/ excluded data	Data period	Missing/ excluded data
Beitbridge	356	---	1970-2001*	---	1971-2001*	---
Bulawayo	587	55	1930-2000	---	1971-2000*	---
Esigodini	627	50	1930-1979 1988-2002*	---	---	---
Figtree	599	37	1990-1999*	---	---	---
Filabusi	555	51	1921-1996	1927, 1928	---	---
Fort Rixon	560	37	1987-2002*	---	---	---
Kezi	455	---	1980-2000*	1985-6	---	---
Marula	563	38	1990-1999*	---	---	---
Mbalabala	627	48	1930-1997	1985, 1995	---	---
Matopos National Park	586	47	1930-1993	1936, 1937, 1980	---	---
Matopos Research Station	597	53	1952-2004	---	1951-1997	---
Mphoengs	484	30	1990-1999*	---	---	---
Mzingwane Dam	622	58	1960-2001	1970, 1999	---	---
West Nicholson	502	---	1975-2003*	---	1980-2000*	---

** These time series were not used for Pettitt tests, as less than 30 years of data were available, or daily data was not available.*

The time series were visually inspected, along with supporting materials such as the station files. The following exclusions were made for each station, in order to remove unreliable data:

- Where data were missing for 2 months or more, the year was excluded
- Where data were missing for 2 weeks or more during the months of November to April (rainy season), the year was excluded
- Where a note had been made in the station file that readings were unreliable (e.g. due to siltation, security), the year was excluded
- Where the runoff coefficient for a given year was more than 1, the rainfall data were checked for correspondence with the next nearest climate station. If this was unsatisfactory, then the discharge data for that year were excluded.
- Where a daily average flow of more than zero but less than 0.02 m^3/s was recorded for 1 month or more, the year's data for 'number of days of no flow' was excluded as being below the detection level of the gauge. The data selected for analysis, following these exclusions, are shown in Tables 2 and 3.

The Multivariate ENSO Index (MEI) used was developed by Wolter and Timlin (1998) from sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature and total cloudiness fraction of the sky. An average MEI for each hydrological year in the period 1951-2005 was obtained from published bimonthly MEI values (Wolter, 2007).

Analyses

A series of non-parametric tests were carried out on several parameters that were derived from the temperature, rainfall, discharge and MEI dataset. For datasets which are not drawn from a population with specific statistical conditions, such as normal distribution, non-parametric tests are appropriate (McCuen, 2003). This is the case for the study data, which is not unusual for hydroclimatic data (Tilahun, 2006). To determine whether there was an overall trend in each time series studied, 2 trend analysis tests were used. The 1st trend analysis test, the Spearman rank test, is a simple measure of correlation between 2 data series and is a special case of the Pearson product-moment coefficient (Myers and Well, 2003). It has often been used for temporal analysis of climatic variables (e.g. Yu and Neil, 1993; González-Hidalgo et al., 2001). The Mann-Kendall test was also applied. This is a more elaborate test for identifying shift trends (e.g. Shao et al., 2009), and compares the relative magnitudes of the data, as opposed to their actual values (Gilbert, 1987). It has been widely used for assessing the significance of temporal trends in hydrological and climatic data (Hirsch et al., 1982), including in semi-arid regions (Zhang et al., 2008).

The time series from each parameter was also subjected to the Pettitt Test (Pettitt, 1979), which is often used to detect abrupt changes in hydrological series (e.g. Shao et al., 2009). The test determines the timing of a change in the distribution of a time series, known as a 'change point' (Zhang et al., 2008). The change point divides the series into 2 sub-series. The significance of the change point is then assessed by F- and t-tests on the change in the mean and the variance. The Pettitt test was used to identify change points in the time series, at a probability threshold of $p = 0.8$, followed by F- and t-tests at 2.5% significance level. This procedure has been used for identifying change points in hydroclimatic data in both humid and semi-arid environments (Tu et al., 2005; Ashagrie et al., 2006; Zhang et al., 2008). Tests were carried out using SPELL-stat v.1.5.1.0B (Guzman and Chu, 2004). To determine whether or not change points that were shown to be significant were also substantively

Table 3
Data sets from the discharge stations used in this study, showing data availability and general characteristics. Data source: hydrological database of the Zimbabwe National Water Authority; permitted upstream use was computed from the water permit database.

Station	River	Catchment area (km^2)	Mean annual unit runoff (mm/a)	Mean flow days per year	Permitted upstream use as % of mean annual runoff	Data period (hydrological years ending)	Missing or excluded data (hydrological years ending)
B30	Mzingwane	448	42	146	6.0%	1959-2004	1962, 1978, 1981-3, 1985-7
B11	Ncema	218	81	186	7.1%	1951-2003	1973, 1999, 2002
B13	Nkankezi	456	55	99	1.6%	1951-2003	1967, 1983-5
B60	Inyankuni	194	53	99	14.6%	1965-2004	1968*, 1975-9*, 1980-2, 1990-1, 1994-5
B61	Inyali	49	47	88	0%	1965-1999	1972, 1974*, 1979, 1980*, 1981-2, 1984-6, 1989, 1991, 1994-5
B74	Jama	75	55	87	0%	1968-2005	1968*, 1969, 1971*, 1974-81*, 1997
B75	Insiza	401	17	120	7.3%	1968-2001	1995
B15	Lumeni	267	75	201	0.2%	1952-2005	1954, 1952-8*, 1968*, 1970, 1986
B39	Mpopoma	91	41	112	0%	1991-9#	none
B64	Ingwizi	712	28	165	0%	1991-9#	1994, 1997
B77	Shashani	539	33	162	0%	1969-2005	1971-2*, 1974, 1975-6*, 1978-9*, 1983*, 1986*, 1988-9, 1991-2, 1994-5, 1999
B78	Zgalangamante	49	47	68	0%	1969-2005	1970, 1971*, 1973-7*, 1980*, 1989-90, 1999-00
B80	Maleme	523	33	126	31.9% ^	1970-2004	1973*, 1976-1984, 1987*, 1988-90, 1992, 1994-5,
B83	Mtshelele	363	48	197	14.8% ^	1970-2004	1971*, 1974*, 1975, 1978-9, 1980*, 1983, 1988*, 1990-1, 1997*, 1999
B87	Mwewe	1 386	10	64	8.4%	1976-2005	1978-80, 1991, 1999

** Only days of no flow data missing*
 # These time series were not used for Pettitt tests, as less than 30 years of data were available.
^ Storage on these rivers is within Matobo National Park and is mainly for non-consumptive use.

important, the effect size was determined. The Cohen's *d* statistic was computed, with values of 0.8 and above considered to have a 'large' effect size (Cohen, 1988).

Using the Southern African hydrological year of October to September, the following time series were prepared from temperature records from Matopos Research Station (for which the longest time series in the region is available):
- Annual average of daily maximum temperature in °C
- Annual average of daily minimum temperature in °C
- Annual maximum (extreme) of daily maximum temperature in °C
- Annual minimum (extreme) of daily minimum temperature in °C

The following time series were prepared for rainfall for all climate stations:
- Annual rainfall in mm/a
- Number of wet days in d/a with rainfall >0.5 mm/d
- Number of heavy rain days per year with rainfall >10 mm/d
- Number of heavy rain days per year with rainfall >20 mm/d
- Number of heavy rain days per year with rainfall >30 mm/d
- Length of longest dry spell for the months November-March (days)
- Number of 5 to 7 d dry spells for the months November to March (-)
- Number of 8 to 14 d dry spells for the months November to March (-)
- Number of more than 14 d dry spells for the months November to March (-)
- Number of more than 20 d dry spells for the months November to March (-)
- Total number of dry spells of 5 d or more for the months November to March (-)

Annual rainfall anomalies were prepared after the method of Hulme et al. (2001) for each station's annual rainfall series. The Thiessen polygon method was applied to estimate catchment rainfall; given the small number of rainfall stations per catchment, a more complex interpolation method was not justified. Catchment rainfall and discharge were compared for each discharge station at an annual time step and for selected stations at monthly and daily time steps.

The following time series were prepared for all discharge stations:
- Annual unit runoff (mm/a)
- Annual maximum of monthly flows (m^3/month)
- Days per annum no flow
- Maximum average daily flow recorded per year (m^3/s)
- Maximum flood recorded (instantaneous flows) per year (m^3/s)
- Runoff coefficient (-)

A simple risk analysis was carried out for each change point where a medium or large effect size had been determined:

$$Risk = P(l > r) \tag{1}$$

where:
P is the probability that load exceeds risk
l is the load: the behaviour of the system under an external stress
r is resistance: the capacity of the system to overcome the load (Ganoulis, 2004)

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For each parameter, a value was taken for resistance based on expert knowledge and related studies; each parameter represented a livelihood or an ecological risk. Thus for the selected parameters, the risk is the probability of occurrence of the below conditions:

- Temperature more than 3.1°C above the long-term mean for Bulawayo, shown to result in reduction of maize yield by 16% (Dimes et al., 2009)
- Rainfall under 450 mm/a, the minimum rainfall recommended for rain-fed maize production (Shumba and Maposa, 1996; Hoffmann et al., 2002)
- Less than 60 and less than 30 wet days per year: representing 1 wet day per 3 days and per 6 days, respectively, in the 6-month rainy season
- Less than 20 days per year with rainfall of over 10 mm/d, often considered the baseline minimum of heavy rainfall events (Lebel et al., 2000; Douville et al., 2001). Heavy rainfall events are very important for runoff generation in an environment with high interception: a threshold of 5 mm/d has been suggested for the study area (Love at al., 2010).
- More than 10 days per year with rainfall of over 20 mm/d, which could result in waterlogging or flooding
- At least 1 dry spell per year lasting over 14 d: dry spells of this length are considered critical in reducing the yield of maize (Lal, 1997; Magombeyi and Taigbenu, 2008).
- At least 1 dry spell per year lasting over 20 d: more extreme than the preceding risk measure
- Annual unit runoff less than 22 mm/a: this is the mean annual unit runoff of the Mzingwane Catchment (Görgens and Boroto, 1997; Chibi et al., 2006)
- Days of no flow more than 219 d/a: this shows the river to be flowing less than 40% of the time.
- Maximum average daily flow recorded per year under 5·m^3/s and maximum instantaneous flood recorded per year under 20 m^3/s: the occurrence of sufficiently large floods annually is important for hydro-ecological processes such as habitat maintenance (King and Louw, 1998). The values selected are indicative as the ecological significance of a specific flow volume or return period is specific to each river, and a detailed analysis is beyond the scope of this paper.

Results

Temperature

Figure 2 summarises the minimum and maximum daily temperature trends observed for 4 locations in the study area, with peaks corresponding with the occurrence of El Niño events (high positive Multivariate ENSO Index - MEI). Similar trends were observed at the 4 locations, but our focus will be on the Matopos Research Station location, which had the longest data set, some 20 years longer. The annual average of maximum daily temperatures at Matopos Research Station (Table 4) showed a significantly increasing trend (Spearman rank test). The Multivariate ENSO Index also shows a significantly increasing trend (Spearman rank test).

Temperature parameters recorded at Matopos Research Station show change points in 1975 and the mid to late 1980s, with the average daily maximum temperature rising from 1975 and the annual average of maximum daily temperatures rising from 1986 (Table 4). A drop in minimum temperatures is recorded from around 1990 onwards.

Table 4
Results of Pettitt test on temperature parameters recorded at Matopos Research Station

Parameter	Significant change (t-test)	Date of Change Point	Effect size (Cohen's d)
Annual mean of the daily maximum temperature (°C)	Rise	September 1975	1.1
Annual maximum of the daily maximum temperature (°C)	Rise	September 1986	1.0
Annual mean of the daily minimum temperature (°C)	Drop	September 1990	2.9
Annual minimum of the daily minimum temperature (°C)	Drop	September 1989	2.6

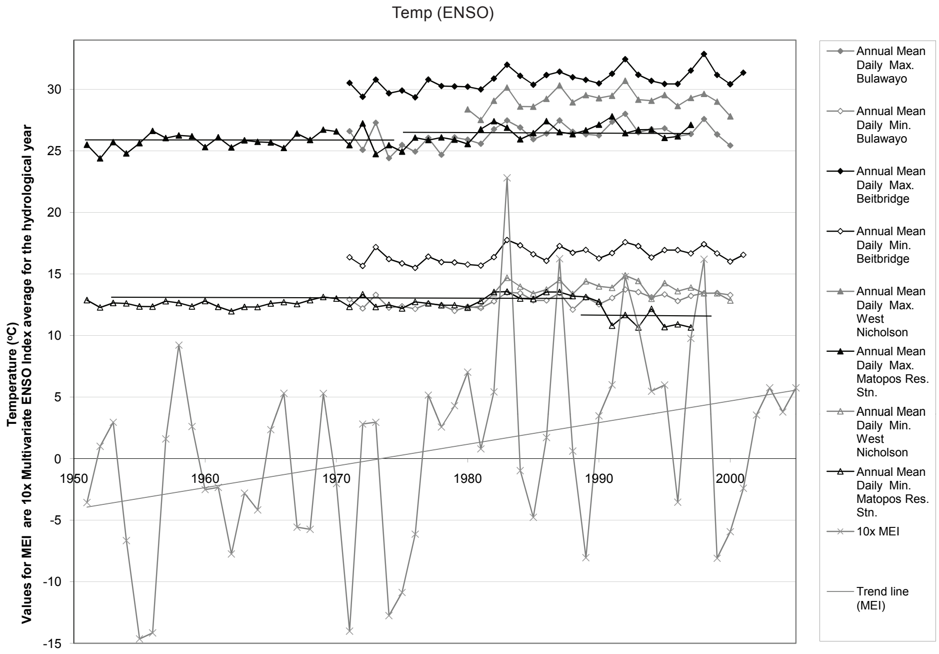

Figure 2
Annual means of daily temperature maxima and minima for 4 stations in the northern Limpopo Basin, Zimbabwe, contrasted with the Multivariate ENSO Index (MEI data: annual averages derived from Wolter, 2007), 1950/51 to 2000/01. The different sub-series for Matopos Research Station (horizontal lines show the sub-series means) are separated from each other by the change points identified in Table 4. For station locations see Fig. 1.

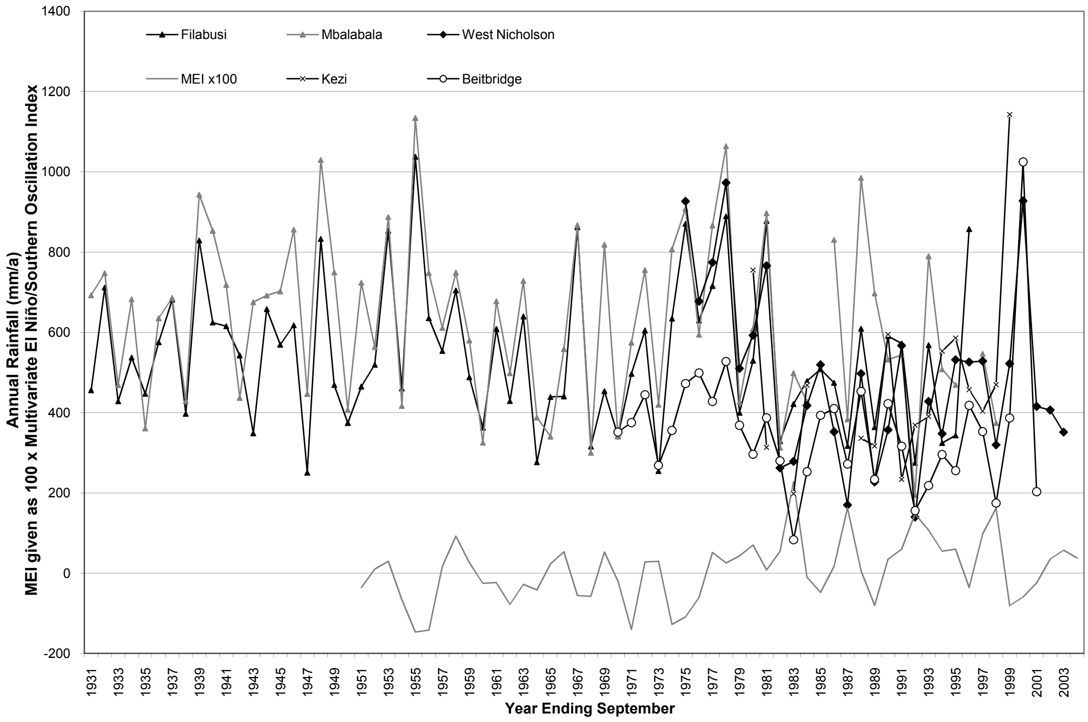

Figure 3
Annual rainfall of selected climate stations in the northern Limpopo Basin, contrasted with the Multivariate ENSO Index (MEI data: annual averages derived from Wolter, 2007), 1931/32 to 2003/04. For station locations see Fig. 1.

Rainfall

The high inter-annual variability of rainfall in the northern Limpopo Basin is similar to that reported for much of Zimbabwe (Twomlow et al., 2006). The influence of the ENSO phenomenon is shown by the correspondence of Multivariate El Niño/Southern Oscillation Index (MEI) peaks with unusually low rainfall for seasons such as 1982/83, 1986/87, 1991/92 and 1997/98 (Fig. 3). For almost all stations there is a strong negative correlation between total annual rainfall and MEI: Mzingwane Dam (r=0.43), Bulawayo (r=0.46), Matopos Research Station (r=0.50), Filabusi (r=0.56), Mbalabala (r=0.56), Kezi (r=0.63), Beitbridge (r=0.70) and West Nicholson (r=0.71). Cyclicity of 17 to 20 years is apparent in the 5-year moving averages and to a lesser extent in the annual rainfall anomalies (Fig. 4).

Spearman rank and Mann-Kendall tests determined that only a limited number of parameters showed a significant drying trend for the whole time series (Table 5). These include the total annual rainfall and days of heavier rainfall at Matopos National Park, as well as the number of longer dry spells at Filabusi and Matopos Research Station. The Pettitt test identified numerous change points, with a significant difference in means confirmed by t-test. The majority showed a medium size effect (0.3 < d < 0.8) and several showed a large size effect (d ≥ 8) (Table 5). Data for Bulawayo and Esigodini did not show significant change points and are not displayed. The majority of these showed a change point to a drier regime from around 1980, with a smaller number of change points that showed a change to a drier regime in the 1960s, as well as around 1980 (see Fig. 6 for examples of the differences identified in Table 5). F-tests showed that most change points also showed a significant decrease in the variance of the rainfall parameter in question. All stations except Bulawayo and Matopos Research Station showed change to fewer wet days. Three stations showed change to an increased number of dry spells, a decreased annual rainfall or both. Only 1 station showed a change to fewer heavy storms. None of the stations showed any change to any wetter regime.

Discharge

The Pettitt test identified numerous change points, with a significant difference in means confirmed by t-test for discharge data obtained from 16 locations in the basin (Table 6). The majority of change points had a large size effect (d > 0.8)Most stations on tributaries of the Mzingwane, Thuli and Shashe Rivers show a change point to a drier regime from around 1980 (see Fig. 6 for examples of the differences identified in Table 6). Most change points also showed a significant decrease in the variability of the parameter in question, confirmed by F-test – although only about half of the stations show a decline in coefficient of variation. Almost all stations showed a change to a smaller number of days of flow and lower annual maximums of average monthly flows.

Many stations showed a consistently drying trend across the full time series for some parameters, including absolute declines in annual unit runoff at 6 stations, confirmed by Spearman rank and Mann-Kendall tests (Table 6). Data for B60 and B87 did not show significant change points and are not displayed. However, data from B87 showed continuous drying trends across the full time series, based on Spearman tests on the annual unit runoff, annual maximum of monthly flows, maximum daily flow per year and maximum flood recorded. Change points detected in B77 occur close to gaps in the time series and these results are also not displayed.

Rainfall-discharge relationships

Only a few discharge stations showed a clear relationship between annual unit runoff and annual catchment rainfall (Fig. 7 and Table 7); these are predominantly tributaries of the Shashe and Thuli Rivers in the west: B77, B78, B80 and B83 (Fig. 1). All of these stations showed change to a drier regime in or around 1980 with at least 1 parameter showing an absolute declining trend across the time series (Table 6), although which parameter showed

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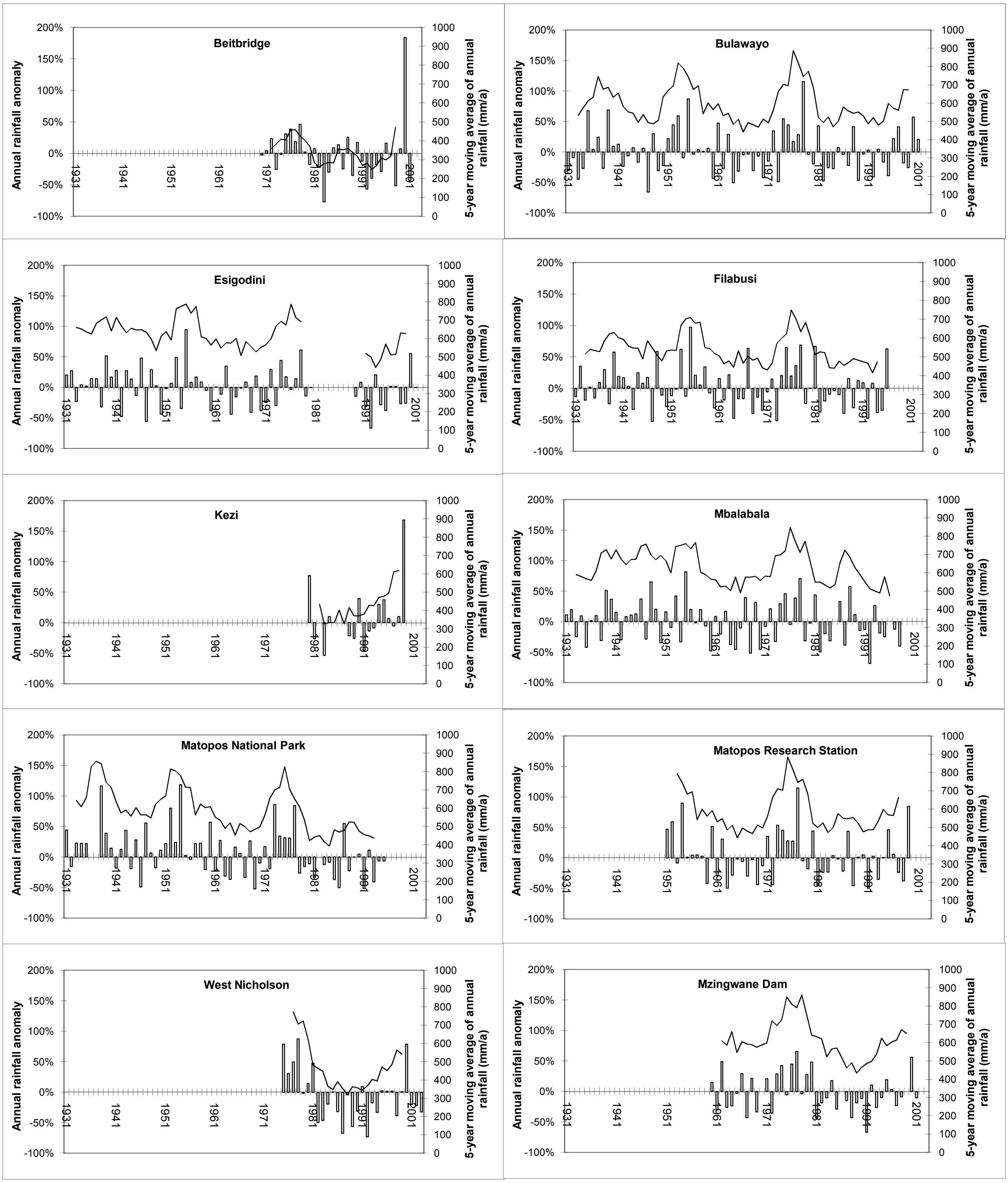

Figure 4
Annual rainfall anomalies (against 1961-1990 mean) and 5-year moving averages for selected climate stations in the northern Limpopo Basin, Zimbabwe, from 1930/31 to 2000/

such a decline is not constant between the stations.

Change over time in the relationship between rainfall and runoff is shown by temporal change in the annual runoff coefficients (Table 7). Three stations show a significant decline in runoff coefficient, across the whole time series, 4 stations show a change to lower runoff coefficients in the early 1980s, and 1 station shows such a change in the mid 1980s. Examination of rainfall-runoff relationships at sub-annual time steps did not give acceptable levels of correlation, probably due to one of the following factors: differences in rainfall and discharge measurement days, delays between rainfall and discharge peaks at a short time step, or the high spatial variability of rainfall in Zimbabwe.

Table 5
Statistical analyses of rainfall parameters recorded, northern Limpopo Basin. Significant change points are illustrated by change in colour in the series on the right of the table: grey represents a reference or homogeneous period, black a wetter period and white a drier period. Cohen's d statistics are shown in italics for a medium effect and in bold for a large effect.

Station	Parameter	Trend analyses: Spearman rank test α = 0.025	Trend analyses: Mann-Kendall test α = 0.025	Change points detected by Pettitt test (p =0.8) and t-test (α = 0.025): Number detected	Effect size: Cohen's d
Filabusi	Annual Rainfall				
	Wet days			1	**0.94**
	Days rainfall >10 mm				
	Days rainfall >20 mm				
	Days rainfall >30 mm				
	Longest Dry spell			2	*0.59* ; *0.33*
	Dry spells 5-7 days				
	Dry spells 8-14 days				
	Dry spells >14 days	Significant increase	Significant increase	2	**0.90** ; *0.79*
	Dry spells >20 days	Significant increase	Significant increase	1	**0.90**
	Dry spells total				
Mbalabala	Annual Rainfall				
	Wet days			1	**1.17**
	Days rainfall >10 mm				
	Days rainfall >20 mm				
	Days rainfall >30 mm				
	Longest Dry spell			1	**0.74**
	Dry spells 5-7 days				
	Dry spells 8-14 days			1	*0.65*
	Dry spells >14 days				
	Dry spells >20 days			1	*0.61*
	Dry spells total		Significant increase		
Mzingwane Dam	Annual Rainfall			1	*0.73*
	Wet days			1	*0.74*
	Days rainfall >10 mm				
	Days rainfall >20 mm			1	**0.83**
	Days rainfall >30 mm				
	Longest Dry spell			1	*0.66*
	Dry spells 5-7 days				
	Dry spells 8-14 days			1	*0.75*
	Dry spells >14 days				
	Dry spells >20 days				
	Dry spells total				*0.76*
Matopos Nat. Park	Annual Rainfall	Significant decrease	Significant decrease	1	*0.68*
	Wet days			1	*0.65*
	Days rainfall >10 mm	Significant decrease	Significant decrease	2	*0.38* ; *0.67*
	Days rainfall >20 mm	Significant decrease	Significant decrease	2	0.27 ; *0.76*
	Days rainfall >30 mm				
	Longest Dry spell				
	Dry spells 5-7 days				
	Dry spells 8-14 days				
	Dry spells >14 days			1	*0.59*
	Dry spells >20 days				
	Dry spells total				

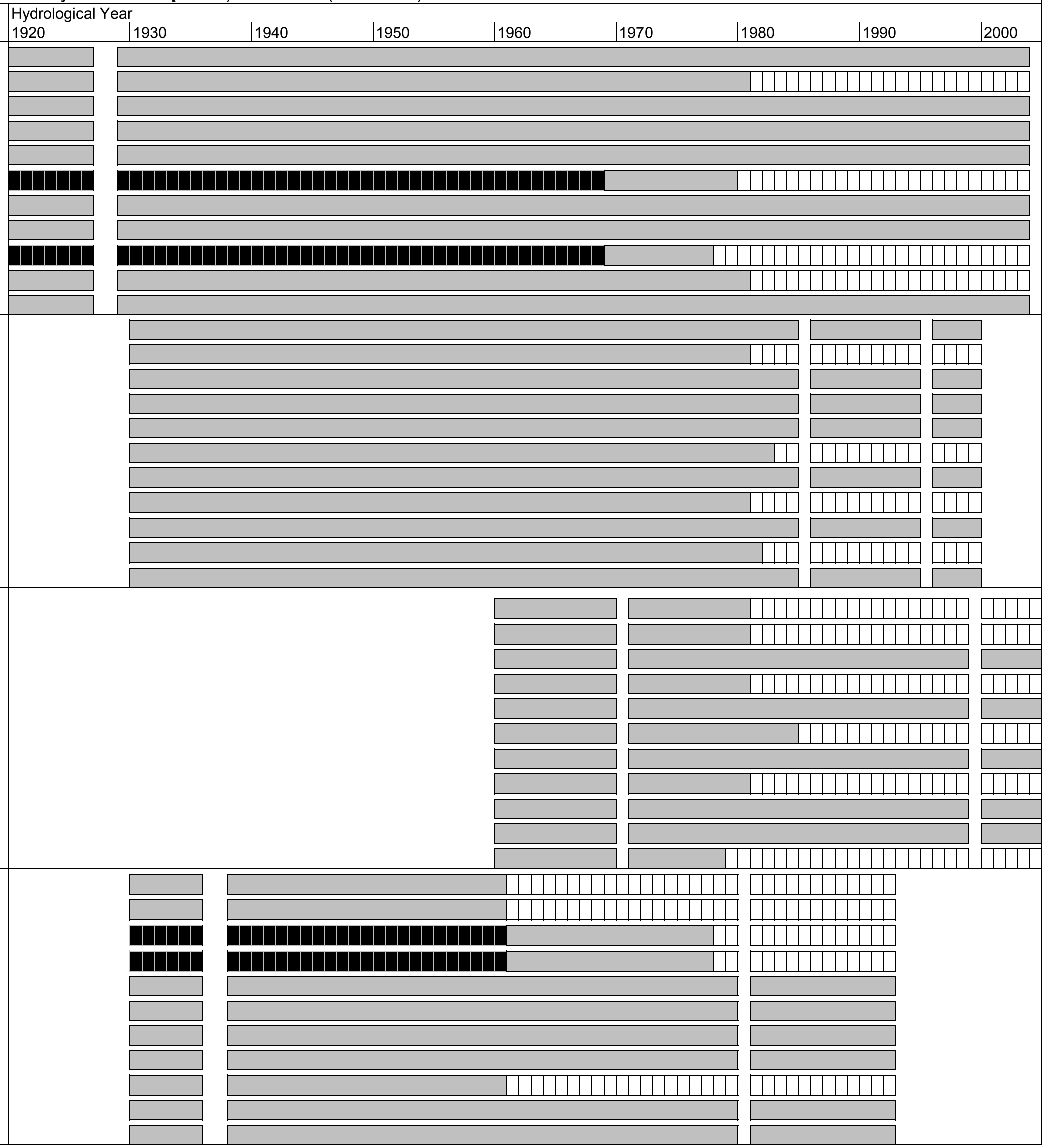

Table 6

Statistical analyses of discharge parameters recorded, northern Limpopo Basin. Significant change points are illustrated by change in colour in the series on the right of the table: grey represents a reference or homogeneous period, black a wetter period and white a drier period. Cohen's d statistics are shown in italics for a medium effect and in bold for a large effect.

Station	Parameter	Trend analyses		Change points detected by Pettitt test (p =0.8) and t-test (α = 0.025)		
		Spearman rank test α = 0.025	Mann-Kendall test α = 0.025	Change Points	Effect size Cohen's d	Hydrological Year 1950 1960 1970 1980 1990 2000
Mzingwane River and Tributaries						
B30, Mzingwane, Mzinyathini	Ann. Unit Runoff					
	Ann. Max. of monthly flows					
	Days per annum no flow			1	*0.76*	
	Max. flood	Significant decrease	Significant decrease	2	**1.11** ; 0.00	
B11, Ncema	Ann. Unit Runoff					
	Ann. Max. of monthly flows			1	*0.73*	
	Days per annum no flow			1	**0.85**	
	Max. flood	Significant decrease	Significant decrease	1	**0.88**	
B13, Nkankezi (Insiza tributary)	Ann. Unit Runoff					
	Ann. Max. of monthly flows					
	Days per annum no flow			1	**0.82**	
	Max. flood			1	*0.61*	
B61, Inyali (Inyankuni tributary), upstream	Ann. Unit Runoff	Significant decrease	Significant decrease	1	**1.11**	
	Ann. Max. of monthly flows	Significant decrease	Significant decrease	1	**0.89**	
	Days per annum no flow			1	**1.12**	
	Max. daily flow		Significant decrease	1	**0.91**	
	Max. flood	Significant decrease	Significant decrease			
B74, Jama (Insiza trib) upstream Upper Insiza Dam	Ann. Unit Runoff	Significant decrease		2	**1.04** ; 0.17	
	Ann. Max. of monthly flows			1	**0.99**	
	Days per annum no flow	Significant increase	Significant increase	1	**1.18**	
	Max. daily flow			1	*0.76*	
	Max. flood	Significant decrease	Significant decrease	2	*0.71* ; *0.58*	
B75, Insiza upstream Upper Insiza Dam	Ann. Unit Runoff			1	**0.90**	
	Ann. Max. of monthly flows			1	*0.65*	
	Days per annum no flow	Significant increase		1	**2.00**	
	Max. flood					
Thuli and Shashe Tributaries						
B15, Lumeni	Ann. Unit Runoff			1	**0.81**	
	Ann. Max. of monthly flows			1	*0.60*	
	Days per annum no flow			1	*0.76*	
	Max. daily flow			1	*0.69*	
	Max. flood			1	**0.92**	
B78, Zgalangamate , upstream of Antelope Dam	Ann. Unit Runoff	Significant decrease		1	**0.91**	
	Ann. Max. of monthly flows			1	**0.85**	
	Days per annum no flow			1	**0.96**	
	Max. daily flow			1	**0.88**	
	Max. flood			1	**0.91**	
B80, Maleme upstream of Maizana Dam	Ann. Unit Runoff			1	**1.69**	
	Ann. Max. of monthly flows			1	**1.78**	
	Days per annum no flow					
	Max. daily flow	Significant decrease	Significant decrease	1	**1.88**	
	Max. flood	Significant decrease	Significant decrease	1	**2.49**	
B83, Mtshelele upstream of Maizana Dam	Ann. Unit Runoff	Significant decrease	Significant decrease	1	**2.47**	
	Ann. Max. of monthly flows	Significant decrease	Significant decrease	1	**2.57**	
	Days per annum no flow			1	**0.93**	
	Max. daily flow	Significant decrease	Significant decrease	2	**1.45** ; **1.19**	
	Max. flood	Significant decrease	Significant decrease	1	**2.09**	

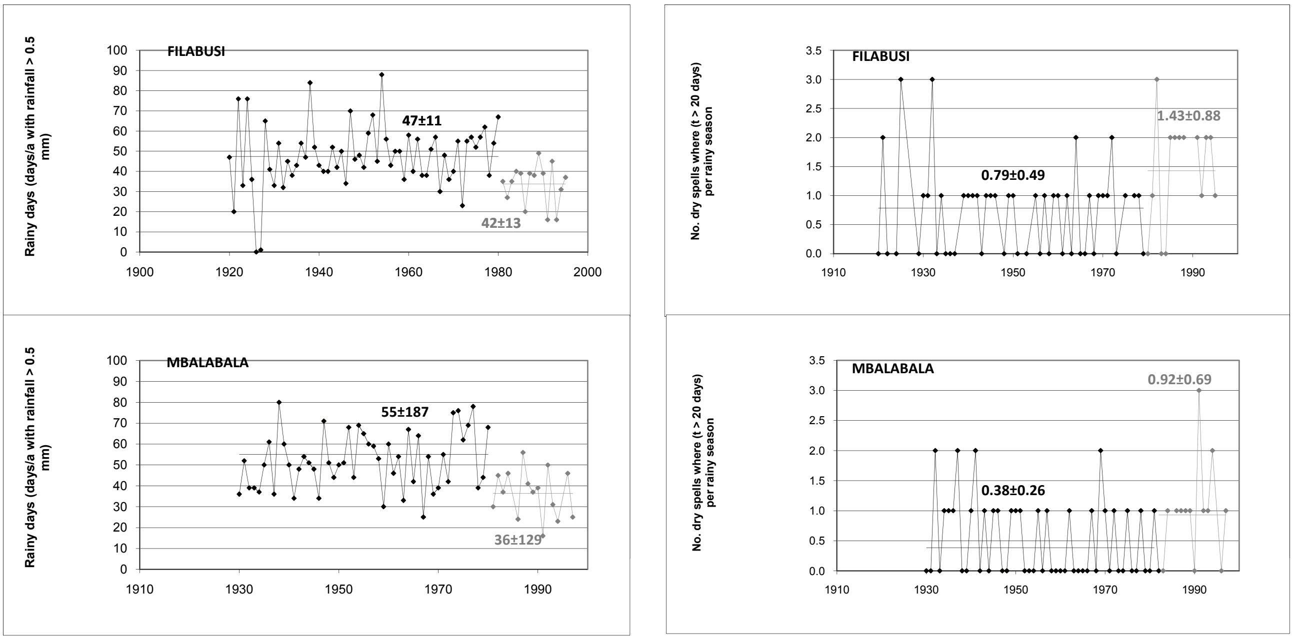

Figure 5
Examples of change points suggesting a possible change from a wetter to a drier rainfall regime: number of rainy days per year (left) and dry spells longer than 20 d (right) recorded at Filabusi (top) and Mbalabala (bottom). The different sub-series (as shown by horizontal lines) are separated from each other by the change points shown in Table 5, identified by Pettitt test and t-test. See Fig. 1 for locations.

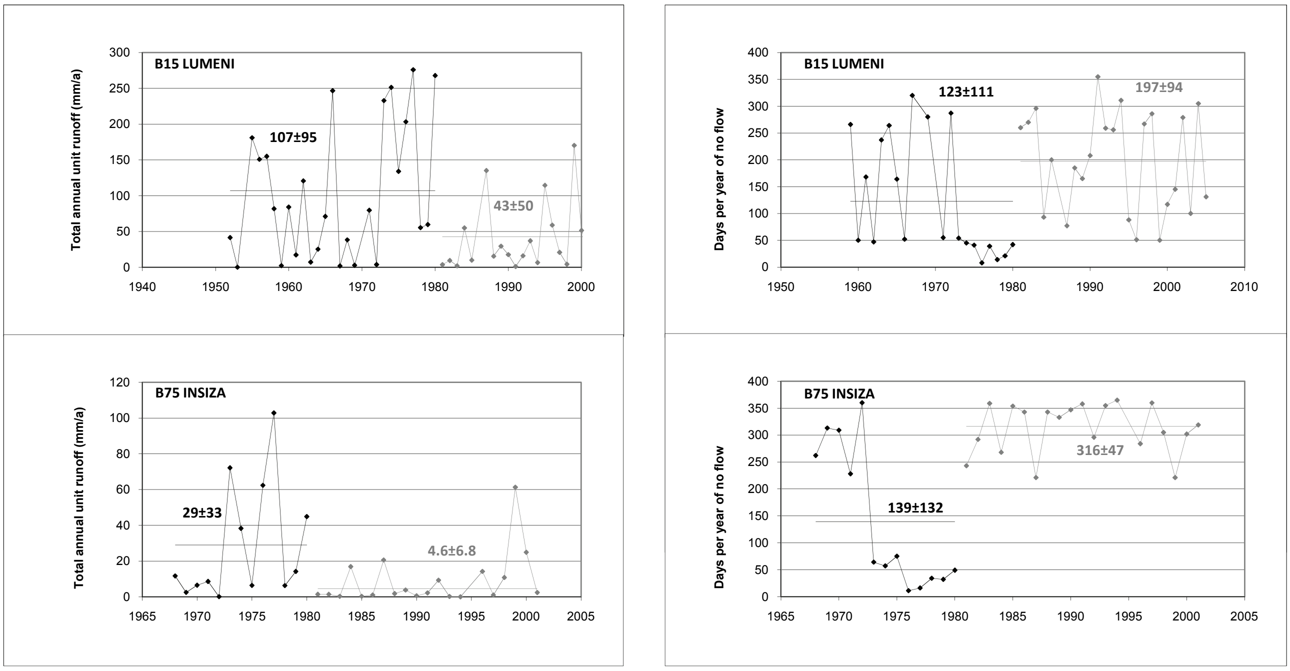

Figure 6
Examples of change points suggesting a possible change from a wetter to a drier discharge regime: total annual unit runoff (left) and number of days without flow per year (right) recorded at B15 Lumeni (top) and B75 Insiza (bottom). The different sub-series (as shown by black or grey lines) are separated from each other by the change points shown in Fig. 7, identified by Pettitt test and t-test. See Fig. 1 for locations.

Risk analysis

The most important climatic risk observed is the increased probability of dry spells, with the probability of dry spells over 14 d and over 20 d rising to above 0.7 in many stations (Table 8). The probability of the number of rainy days per year falling below 60 and below 30 also increased substantially after each change point (mainly in 1979/80). There is no substantive risk posed by temperature and little increase in risk posed by annual rainfall levels. The probability of heavy storms declined at the 2 stations for which statistically significant change was observed.

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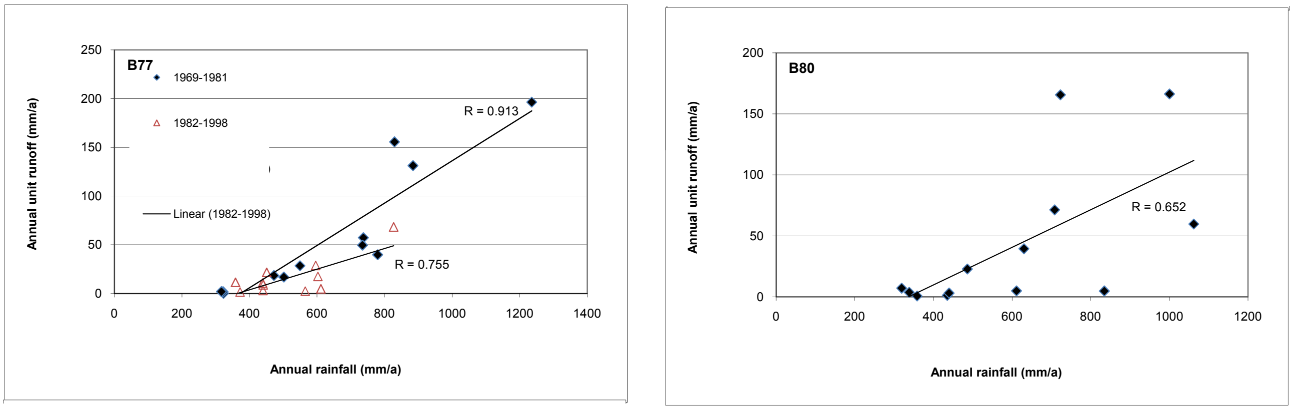

Figure 7
Correlation of annual catchment rainfall with annual discharge recorded at the 4 discharge stations in the northern Limpopo Basin, Zimbabwe that show a high correlation: those where r > 0.6. They are all from the west of the study area (see Fig. 1 for locations). r = correlation coefficient.

Table 7
Rainfall-discharge relationships in the study area at an annual time step. Correlation coefficients were determined between the annual rainfall and annual unit runoff for each discharge station. The significance of any trend in the annual runoff coefficients for each discharge station was assessed using Pettitt Test (*P*=0.8), t-test (2.5% significance) and Spearman Rank Test (2.5% significance).

Discharge station	Rainfall stations (contributions to Thiessen polygons for discharge station)	Correlation coefficient	Trend in annual runoff coefficient
B30, Mzingwane River at Mzinyathini	Esigodini (0.36) Matopos Research Stn (0.34) Bulawayo (0.30)	0.289	No significant trend
B11, Ncema River	Esigodini (0.86) Bulawayo (0.14)	0.066	No significant trend
B13, Nkankezi River	Filabusi *	- 0.176	No significant trend
B15, Lumeni River	Mbalabala *	0.108	Significant change point: decrease in value of runoff coefficient, Sept. 1980
B39, Mpopoma River	Figtree (0.54) Matopos National Park (0.38) Matopos Research Stn (0.08)	0.857	No significant trend
B60, Inyankuni River	Esigodini (0.89) Mbalabala (0.11)	- 0.088	No significant trend
B61, Inyali River	Mbalabala (0.93) Esigodini (0.07)	-0.110	Significant overall decline in value of runoff coefficient. Significant change point: decrease in value of runoff coefficient, Sept. 1987
B64, Ingwizi River	Marula (0.70) Mphoengs (0.30)	0.830	No significant trend
B74, Jama River	Esigondi (1968-1987)* Fort Rixon (1988-2001)*	0.157	Significant change point: decrease in value of runoff coefficient, Sept. 1981
B75, Insiza River	Esigondi (1968-1987)* Fort Rixon (1988-2001)*	0.010	No significant trend
B77, Shashani	Matopos Nat. Park (1969-1979)* Kezi (1980-1998)*	0.887	Significant change point: decrease in value of runoff coefficient, Sept. 1982
B78, Zgalangamate	Matopos Nat. Park (1969-1979)* Kezi (1980-1998)*	0.838	No significant trend
B80, Maleme	Matopos Nat. Park*	0.652	Data set too small (13 points)
B83, Mtshelele	Matopos Nat. Park*	0.775	Significant change point: decrease in value of runoff coefficient, Sept. 1982
B87, Mwewe	West Nicholson*	0.363	Significant overall decline in value of runoff coefficient

** Sole nearest rainfall station from Thiessen polygon for whole or part of time series*

Table 8
Risk analysis of climate parameters, comparing probability in series before and after identified change points (Table 5). For parameters where more than one change point was identified at a given station, the change point with the large effect size was selected.

	Filabusi		Mbalabala		Mzingwane Dam		Matopos	
Risk	**Series 1**	**Series 2**	**Series 1**	**Series 2**	**Series 1**	**Series 2**	**Series 1**	**Series 2**
Temperature 3.1°C above average							0.00	0.00
Rainfall under 450 mm/a					0.20	0.21	0.17	0.39
Less than 30 wet days per year	0.07	0.27	0.02	0.27	0.00	0.05	0.00	0.12
Less than 60 wet days per year	0.85	1.00	0.67	1.00	0.40	0.74	0.79	0.88
Less than 20 d/a with rainfall > 10 mm							0.54	0.06
More than 10 d/a with rainfall > 20 mm					0.35	0.16	0.33	0.06
At least 1 dry spell per year lasting more than 14 d	0.86	0.89					0.79	0.91
At least 2 dry spells per year lasting more than14 d	0.50	0.89					0.55	0.73
At least 1 dry spell per year lasting more than 20 d	0.58	0.79	0.44	0.71				
At least 2 dry spells per year lasting more than 20 d	0.10	0.57	0.08	0.14				

Table 9
Risk analysis of discharge parameters, comparing probability in series before and after identified change points (Table 6). For parameters where more than one change point was identified at a given station, the change point with the large effect size was selected.

	Risk	**Annual unit runoff > 22 mm/a**	**Annual maximum of monthly flows < 1 m³/month**	**No flow > 219 d/a**	**Maximum average daily flow recorded per year < 5 m³/s**	**Maximum flood recorded (instantaneous) per year < 20 m³/s**
B30 Mzingwane	Series 1			0.47		0.07
	Series 2			0.88		0.27
B11 Ncema	Series 1		0.12	0.29		0.36
	Series 2		0.17	0.68		0.45
B13 Nkankezi	Series 1			0.54		0.15
	Series 2			0.90		0.39
B61 Inyali	Series 1	0.38	0.69	0.73	0.50	
	Series 2	0.82	0.91	0.91	0.92	
B74 Jama	Series 1	0.18	0.55	0.70		0.36
	Series 2	0.68	0.82	0.92		0.73
B75 Insiza	Series 1	0.62	0.15	0.38		
	Series 2	0.90	0.65	1.00		
B15 Lumeni	Series 1	0.26	0.25	0.30	0.19	0.22
	Series 2	0.54	0.41	0.46	0.32	0.54
B78 Zgalangamate	Series 1	0.39	0.72	0.94	0.39	0.44
	Series 2	0.71	1.00	1.00	0.71	0.79
B80 Maleme	Series 1	0.17	0.17		0.00	0.00
	Series 2	0.92	0.67		0.82	1.00
B83 Mtshelele	Series 1	0.25	0.13	0.17	0.00	0.14
	Series 2	0.80	0.75	0.55	0.60	0.71

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There is a high risk of low annual runoff occurring. The probability of the overall Mzingwane Catchment average unit runoff exceeding a study catchment's annual unit runoff doubled at most stations after the change points (Table 9). At all stations except B80, the probability of the river flowing less than 40% of time has increased substantially since the change points. In most cases, the probability of lower maximum flows and floods has increased.

Discussion

Stationarity of the climatic and hydrological time series

The general trends in the time series, as identified by Spearman rank and Mann-Kendall tests, observed in the northern Limpopo Basin and the significant change points indicate:

- The relationship between rainfall and temperature and ENSO (Figs. 2 and 3); see also Alemaw and Chaoka (2006)
- An increase in maximum daily temperatures (Table 3); see also New et al. (2006)
- A decline in rainfall (Table 5 and Fig. 5) with high inter-decadal variability (Fig. 4); see also Trenberth et al. (2007)
- A 3- to 5-year cyclicity in rainfall (Fig. 4), similar to and Jury and Mpeta (2005) and possibly related to El Niño. This cycle could be contained within a 17- to 20-year cyclicity in rainfall (Fig. 4) which could be similar to Tyson (1986) and Mason et al. (1997). Thus, there is possibly a shorter cycle within a longer cycle.

The vast majority of climate stations showed a change towards a drier climate from the early 1980s (Table 5) – the notable exception being Bulawayo, which is at a higher elevation and actually outside the Limpopo Basin. Decreased land rainfall from this period onwards was reported at global level by Trenberth et al. (2007). Decline in rainfall reflecting a new rainfall regime, as opposed to a gradual decrease, has also been reported from western Australia (Hope et al., 2006).

A corresponding change to a drier regime was also observed for most discharge stations (Table 6), notably from the early 1980s in the stations upstream of major dams (Mzingwane, Shashe and Thuli tributaries; see Fig. 1 for locations). Such change in runoff regime has not been previously reported in south-eastern Africa. In 6 of the 16 stations (there is no consistent geographical pattern), there was a significant decline in annual unit runoff for the full time series. The change to a regime of relatively lower or less frequent rainfall and discharge demonstrates that water resource availability has shown a decline in the northern Limpopo Basin in the last half-century, even if trends in parameters such as annual rainfall are obscured in many places by the observed cyclicity.

Causes of change in rainfall and discharge

The decline in rainfall and other drying trends in rainfall parameters (Table 5) could be related to:

- The increasing frequency and severity of El Niño events (Alemaw and Chaoka, 2006).
- Changes due to global warming: the more pronounced increase in number of dry spells with more limited changes in total rainfall is similar to those predicted from global circulation models by Christensen et al. (2007) for Southern Africa. The median precipitation response predicted is zero for December to May rainfall with a 13% decline in September to November rainfall (in southern Zimbabwe there is often very little rainfall during September and October). The number of dry spells are predicted to increase in most subtropical areas.
- Possible effects of land use change on moisture recycling. Large areas of Zimbabwe, including parts of the study area, have experienced significant population growth, agricultural intensification and loss of forest cover in the last 50 years (e.g. Mapedza et al., 2003; Zinyama and Whitlow, 2004). However, changing sea surface temperatures (and thus ENSO) are thought to be more important than changing land use patterns in controlling warm season rainfall variability and trends in Southern Africa (Christensen et al., 2007). This needs further research.
- Observed cyclicity in rainfall: Fig. 5 shows that the early 1980s are at the lower point of the 5-year moving average of annual rainfall. However, the cyclicity exhibited would suggest another change point (to a wetter regime) would be expected by the late 1990s. Such a change could not (yet) be observed, but may become apparent once more recent data become available.

The change to a drier regime in many discharge stations (Table 6) could be related to the following factors:

- Declining rainfall, as observed in Fig. 5, resulting in declining runoff generation. This explanation is favoured by the observed co-incidence of change points to decreasing rainfall and decreasing discharge in the early 1980s.
- Increased upstream withdrawals due to small dam construction. The Zimbabwe Government carried out an extensive dam-building programme; an estimated 15 000 small dams were built in Zimbabwe in the early to mid 1980s (e.g. Jewsbury and Imevbore, 1988; Chimomwa and Nugent, 1993).
- Post-1980 increases in agricultural water use, which will have occurred due to increased production since independence in 1980, at both smallholder and commercial scale (Thirtle et al., 1993), as well as due to changing population distribution, especially in areas which had experienced population displacement during the civil war (Zinyama and Whitlow, 2004).
- Possible effects of land-use change on hydrology: increasing population density and conversion of forest or rangeland to agricultural land, which has occurred in Zimbabwe over the past 50 years, see above, can cause a decrease in runoff (e.g. Calder et al., 1995) – although it can also cause an increase in runoff (e.g. Bari and Smettem, 2004).

Rainfall-runoff relationships

It should be noted that correlation of runoff with catchment rainfall will have been weakened by poor rainfall station distribution in the study area. Only a few discharge stations showed a good correlation (B77, B78, B80 and B83; see Table 7). These stations are all from the west of the study area (see Fig. 1), where small dams are fewer, farm sizes are larger and crop production is minimal (Surveyor General of Zimbabwe and Forestry Commission, 1996); thus abstractions by farmers are likely to be lower in these areas. Seven discharge stations spread across the study area (B15, B40, B61, B74, B77, B83 and B87, Table 7) have declining runoff coefficients, showing a possible change in the runoff generation regime. Field studies, using experimental catchments with rainfall measured from several stations within the catchment, rather than interpolated from the national rainfall stations used in this study, might assist in further understanding of this problem.

Risk analysis

The principal livelihood risks posed by the changing hydroclimatic patterns observed are: risk of rainfed crop failure, due to an increasing probability of dry spells over 14 days and 20 days in length (Table 8), and risk to water supply (for agriculture and domestic use) from an increasing probability of annual unit runoff dropping below the Mzingwane Catchment average (Table 9). The changes in temperature and total annual rainfall do not appear to impose risk at this time. Changing flow regimes, with a higher probability of smaller-sized floods, may have ecological implications, but this cannot be assessed without a full flood analysis.

Conclusions

There is a complex variety of factors that may influence the temporal distribution of rainfall and discharge in southern Africa, some of which result in cyclicity. This complexity may be part of the reason that hydroclimatic studies using different statistical techniques make different findings. For example, Mazvimavi (2008) did not detect significant change in extreme high or low rainfall in 40 stations across Zimbabwe, using the Mann-Kendal test and quantile regression analysis. However, this study has shown that, in terms of the statistical tests selected in this study, total seasonal rainfall and annual discharges in the northern Limpopo Basin, Zimbabwe, have shown notable declines since 1980 at many measuring stations. The evidence from the time series analyses shows a declining rainfall trend that appears to be related to the increased incidence and severity of El Niño events and to changes associated with global warming. Discharge has been reduced by the declining rainfall input, but also by declining runoff generation in headwater catchments, likely due to impoundments in small dams and increased abstractions for irrigated crop production, especially in the north and east of the study area. If rainfall continues to decline, it is likely that a multiplier effect will be felt on discharge, due to non-linear processes resulting in more than proportional declines in discharge (De Wit and Stankiewicz, 2006), as well as increased agricultural water abstractions by farmers in the headwater catchments to compensate with irrigation for the reduced rainfall.

It has been seen that since 1980 water resource availability in the study area has declined, both in terms of total annual water available for storage (i.e. declines in annual rainfall, annual unit runoff) and in terms of the frequency of water availability (i.e. declines in number of rainy days, increases in dry spells, increases in days without flow). Although construction of dams can mitigate inter-annual variability and the declining frequency of water availability, the decline in total annual water available for storage will decrease the yield of dams. These trends make it unlikely that the construction on the Mzingwane River of the proposed Glassblock Dam (Chibi et al., 2006), located between Mbalabala and West Nicholson (see Fig. 1), would be beneficial, and will further stress urban water supplies in the study area, notably those of Zimbabwe's second-largest city of Bulawayo, which already experiences chronic water shortages (Gumbo, 2004). Further downstream, the proposed expansion of irrigation from Zhovhe Dam to provide for smallholder cereal production as well as cash crops may also be compromised, along with the proposed transboundary water supply to Musina in South Africa. Taken together, these trends suggest that water supply development for south-western Zimbabwe (including any water exports from Zimbabwe) should focus on alternatives to the Mzingwane Catchment and the Limpopo Basin. It would be strategic to link such alternatives to the long-awaited Matabeleland-Zambezi water carrier.

Drought and subsequent crop failure is becoming an all too common feature of south-eastern Africa (Richardson, 2007). This study has shown a rising risk of crop failure, due to an increasing probability of dry spells longer than 14 days occurring. Declining water resource availability in the region has had, and will undoubtedly continue to have, dramatic impacts on staple food production and food security (Du Toit and Prinsloo, 2001; Stige et al., 2006). The declining frequency of water availability will make the situation worse, and it has been shown that, at least for some parts of the study area, there is an increasing risk of annual runoff below the long-term catchment average. Unfortunately, many strategies to address hunger in southern Africa are water intensive, and some have been shown to result in water use conflicts (Love et al., 2006). Such initiatives should be complemented by interventions that maximise the use of the existing scarce water resources. These include soil water conservation techniques (e.g. Mupangwa et al., 2006), rainwater harvesting (e.g. Mwenge Kahinda et al., 2007), improving the management of existing irrigation schemes (e.g. Samakande et al., 2004) and the use of alternative crops – such as switching from maize to sorghum – when a drier season is to be expected based on the condition of the ENSO phenomenon (Stige et al., 2006).

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