The 1950-1998 warm ENSO events and regional implications to river flow variability in Southern Africa

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Abstract

The variability of annual river runoff and its possible association with the 1950-1998 seasonal El Niño/Southern Oscillation (ENSO) is investigated in 502 rivers gauged in 9 countries of the Southern African region. We found some evidence of possible links between available surface water resources in terms of mean annual runoff and warm ENSO events. This was revealed by the existence of strong and nearly-strong positive linear correlation between annual discharges and the warm seasonal ENSO indices explained by the sea level pressure (SLP) data. Of the 502 rivers we considered, 150 rivers exhibit strong positive correlation between the December to February quarter ENSO indices and the annual runoff – with 25% of the variance in annual runoff being accounted for by the warm ENSO events. A relatively weaker positive correlation also occurred in 174 rivers we considered. The strong positive correlation occurs in parts of Zambia, Namibia, Mozambique and the lowveld in South Africa. In these parts of Southern Africa, there is evidence of a general decline in annual runoff after the mid-1970s compared to the period before it. These revelations are explored and are found to be partly explained by the high frequency of drought-related warm ENSO phenomena that occurred during the same period.

Keywords: river flow variability, ENSO, correlation analysis, Southern Africa

Introduction

Significant correlations between large-scale regional precipitation patterns and ENSO episodes have been identified for several specific regions around the world (e.g., Jury, 2003; Chiew et al., 1998; Ropelewski and Halpert, 1987). On a seasonal time-scale, the ENSO phenomenon (Zhang et al., 1997) affects the atmospheric circulation outside the tropics (Philander, 1990), and south-eastern Africa tends to experience dry conditions during warm ENSO events (Jury, 2003; Ropelewski and Halpert, 1987). ENSO is an atmospheric phenomenon that has long been known to have a characteristic manifestation in Southern Africa whereby warm-phase episodes are associated with droughts while cold-phase episodes lead to wetter than normal conditions. Mechanisms linking above-normal sea-surface temperature (SST) anomalies over the central Indian Ocean with Southern African droughts have also been explored (Jury and Pathack, 1991; 1993; Landman, 1995; Jury et al., 1996; Tennant, 1996; Landman and Klopper, 1998; Rautenbach, 1998).

The ENSO phenomenon is one of the biggest players in the game of year-to-year climatic variability. As many researchers have now come to appreciate, these two phenomena typically occur in conjunction, about once every few years. The influence of ENSO events is profoundly felt outside the tropics as well (Jury, 2003; Rautenbach, 1998; Landman and Klopper, 1998). A predictive model for the December to March rainfall season simulation for South Africa that considers ENSO influence in a canonical correlation analysis is provided in Landman and Klopper (1998). Due to the heterogeneous nature of rainfall, a large number of measurement stations are required for accurate characterisation of rainfall patterns over large areas. River systems are comprehensive integrators of rainfall over large areas. Therefore, the ability to predict flow patterns in rivers will be highly enhanced if a strong relationship between river discharge and ENSO exists, and is quantified. Furthermore, understanding of large-scale global atmospheric dynamics will enhance our understanding of regional/local systems of rainfall occurrence, which could improve understanding of river flow characteristics.

In an attempt to address the relationship between ENSO and the natural variability in the flow of tropical rivers, Amarasekera et al. (1997) studied the Amazon, Congo, Parana and Nile Rivers. They investigated the existence of a stronger correlation between the annual discharges of these rivers and seasonal SST indices. A prevalence of below-normal rainfall occurrences in several regions of South Africa during El Niño years has been reported (e.g. Landman and Klopper, 1998; Rautenbach, 1998). Recent studies indicate that ENSO events can be accurately predicted one to two years in advance using a physical model of the coupled ocean-atmospheric system (Chen et al., 1995). Therefore, the motivation of this paper is to explore whether a relationship exists between river discharge and ENSO and to quantify the relationship in the Southern African river systems. Emphasis is given to the warm ENSO events to examine the possible link with the decline in runoff of this region in the period after the mid-1970s (Alemaw et al., 2001).

In this paper the relationship between seasonal quarter warm ENSO events in terms of the SLP anomalies data and annual discharge of the 502 rivers in the Southern African region is examined. The seasonal quarter ENSO indices are the three-month aggregate mean values of December to February (DJF), March to May (MAM), June to August (JJA) and September to November (SON). This analysis is specifically aimed at investigating the type and magnitude of possible correlations between warm ENSO events and the regional implications of the annual discharge of rivers over the Southern African region. Possible explanations are also presented for the possible link between the long-term ENSO patterns and trends in annual runoff pattern and the

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Plants of economic importance, e.g. grazing, woods, as well as Hoodia, !Ghabba, Devil's claw, etc. -- distribution, use and marketing	Bertus/Carole
Rhigozum trichotomum, Acacia nilotica	Ngula/Carole/Patrik
Prosopis and other aliens along the Orange and Fish Rivers; reeds choking channels downstream of Hardap	Carole
Identify biodiversity hotspots	Carole/Ngula
Past and current distribution of species -- importance for conservancy planning and protected areas	Carole/Ngula
Overall, plants and mammals	Carole/Ngula
Species and distribution; present aquaculture and potential; fishery potential	Specialist/Carole
With a view for ancient history and areas of interest	Historian?
Detailed history of the area and map of sites of historical interest	Historian?
Changes in land allocation and history behind it	Carole/Ngula/historian
	Carole/Ngula
	Carole/Ngula
	Carole/Ngula
	Carole/Ngula
	Carole/Ngula
	Carole/Ngula
Update with respect to resettlement farms, communal areas -- where, who, ownership; tenure	Wolfgang Werner
	Carole/Ngula
	Wolfgang Werner/ Carole / Ngula / Salomon
Types	Bertus
	Bertus
Update through vet services	
Update through vet services	
Update through vet services	
Update through vet services	

TABLE 1 Study catchments used in the study			
Country	No. of Sites	Catchment area, km²	Proportion to total area, %
Botswana	13	39 493	2.6
Malawi	24	51 088	4.8
Mozambique	14	1 912 669	2.8
Namibia	26	1 026 922	5.2
S. Africa	260	1 673 838	51.8
Swaziland	22	35 029	4.4
Tanzania	47	63 856	9.4
Zambia	24	1 042 521	4.8
Zimbabwe	72	390 083	14.3
Total	**502**	**6 235 499**	**100.0**

spatial coherence of the ENSO-discharge correlation over the region. Even though ENSO is quantified in terms of two different indices, namely, SST and the sea-level pressure (SLP), in this study we have used the SLP anomaly data, which are also commonly used in the climate research community (e.g. Smith and Sardeshmukh, 2000; Jury, 2003; Rautenbach, 1998).

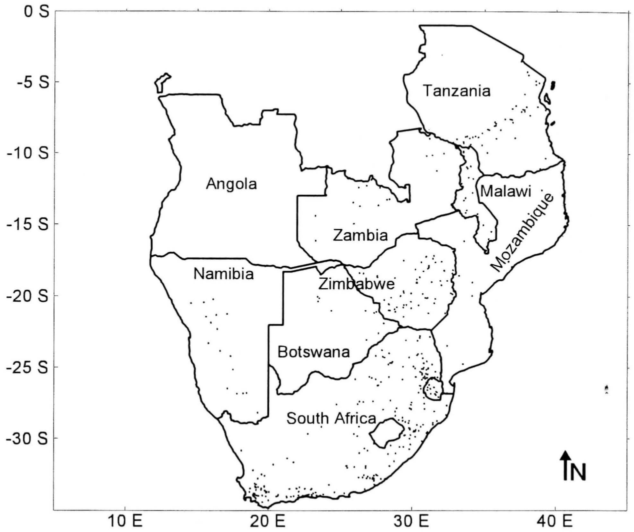

Figure 1
Location map and distribution of discharge gauging stations in the Southern African region used in the study

Data used

River flow data of 502 gauging stations from nine Southern African countries were acquired from the database of FRIEND (Flow Regimes from International Experiments and Network Data) Project coordinated at the University of Dar es Salaam. Quality of daily discharge data was checked and then annual runoff was extracted. The details of the data are summarised in Table 1. The catchments considered for this study have data records longer than 15 years. The location of the 502 chosen gauging stations used is presented in Fig. 1. The density of gauging stations is one station in every 6 060 km² in South Africa and Swaziland compared to one station in 20 575 km² for the rest of the region. The density of gauged catchments (Table 1) outside the Republic of South Africa and Swaziland is not sufficient to draw definite conclusions regarding spatial variability of river flow in the region and its possible correlation with ENSO phenomena. In the FRIEND database, discharge data for the 502 rivers were available from early 1950s up to 1998, and hence the study covered only this period. As more data that extend to 2005 become available the study could reveal the recent phenomena. Therefore, this study may be treated only as a preliminary investigation.

Monthly dataset of SLP anomalies are acquired from database of the National Oceanographic and Aeronautics Administration (NOAA) and are acquired from the Climate Prediction Centre (CPC) official web site. Figure 2 depicts the monthly SLP anomalies for the period from January 1950 to April 1998 expressed in standard units, which is a measure of the pressure difference between the central (Tahiti) and western Pacific (Darwin).

Coincident periods for both ENSO events and discharge were selected and analysed. Of the 16 El Niño events that have occurred in the century just ended, 8 of the strongest historical El Niño events have occurred since the 1950s. These have been recorded and much research is documented (e.g. Zhang et al., 1997; Philander, 1990). The years are from December to January of 1952/53, 1956/57, 65/66, 72/73, 82/83, 86/87, 91/92 and 97/98. These El Niño years are similar to those defined by other researchers (e.g. Amarasekera et al., 1997; Chiew et al., 1998). The selected periods were each split into 4 consecutive

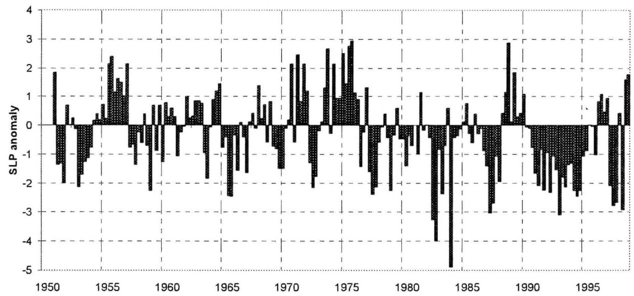

Figure 2
Time series plots of aggregated 3-month mean sea-level pressure (SLP) anomalies expressed in standard units for December 1950 to April 1998 [Data source: NOAA]

three-month quarters of December to February (DJF), March to May (MAM), June to August (JJA) and September to November (SON). The main reason for creating different subsets was to better capture the influence of ENSO on the rainfall as a proxy for catchment-hydrological response and by inference river discharge.

Methodology

The methodology used in this study comprised correlation analysis of the mean annual runoff and three-month quarter warm ENSO indices during the concurrent El Niño years considered. The seasonal cycle of each river is defined as a 12-month period starting from the month of lowest average discharge for each year. For each of the 502 rivers, the average monthly discharge is calculated and then the seasonal cycle of flow and the annual flow volume are determined. The type and magnitude of the correlation is also investigated. We have also attempted to explore the possible evidence of a link between the long-term ENSO patterns and trends in annual runoff pattern across the region of Southern Africa.

The variance accounted for by El Niño in the natural variability of river discharge of selected drainage basins in Southern Africa is established. In order to avoid possible lag correlation between seasonal discharges and seasonal SLPs, a correlation

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Temperature regimes at coast and inland	
Temperature regimes at coast and inland	
Temperature regimes at coast and inland	
Coastal and inland, summer and winter	
Coastal and inland, summer and winter	
This section probably deserves more detail and interpretation; get in expert in the south?	Specialist?
Also get from SA for the Orange River	with stakeholdrers Carole/Ngula
Update monthly flow for long-term stations	Carole/Ngula
Update monthly flow for long-term stations	Carole/Ngula
Get daily rainfall and flow data for peak periods and episodic events	Carole/Ngula
Monthly totals and then daily for episodic events	Carole/Ngula
Satellite images	Ngula
Use	Specialist?
Update with info from DWA (Keetmanshoop), Arnold Bittner	Carole/Ngula
Update with info from DWA (Keetmanshoop), Arnold Bittner	Carole/Ngula
Salt block info from DWA	Carole/Ngula
Basic biomes of the area; update with John Irish?	Ngula/Carole/Patrik
Have a good understanding of veg types, their composition and use as a resource	Ngula/Carole/Patrik
Have a good understanding of veg types, their composition and use as a resource	Ngula/Carole/Patrik
Understand the variation in biomass between good and bad years	Ngula/Carole/Patrik

TABLE 2 Coefficients of cross-correlation between quarterly SLP anomalies and mean annual discharge during El Niño years of a river at station 65312109 in Malawi	
Season	**Cross-correlation, r**
Jun,Jul,Aug (-)	**-0.57**
Sep,Oct,Nov (-)	**-0.51**
Dec,Jan,Feb	**0.52**
May,Apr,May	0.47
Jun,Jul,Aug	0.24
Sep,Oct,Nov	0.43
Dec,Jan,Feb (+)	**-0.45**
Mar,Apr,May (+)	**-0.79**
(-) quarters preceding El Niño year (+) quarters following El Niño year Confidence intervals as per Figure 3	

analysis is conducted with the annual discharge, against eight quarters of SLP anomalies. Eight quarters are formed from four SLP quarters during El Niño years, and two quarters each before and after El Niño years.

We measured the association between ENSO and river discharges using the linear correlation coefficient, r (also called the product-moment correlation coefficient, or Pearson's r). In order to assess whether a correlation is significant, we use the test statistic, t, to identify the confidence level of the correlations between ENSO and the terrestrial hydrologic variable of river discharge. The test statistic, t, is defined by Hirsch et al. (1993) as:

$$t = r\sqrt{\frac{N-2}{1-r^2}} \qquad (1)$$

is distributed in the null hypothesis case (of no correlation) like Student's-distribution with v = N-2 degrees of freedom. The confidence level, γ for t (r,v) is then computed as given in Press et al. (1992) as follows:

$$\gamma(t,v) = \int_{-t(r,v)}^{t(r,v)} f(t,v)\,dt \qquad (2)$$

By combining Eqs. (1) and (2), the confidence interval, β = (1-γ)100% is computed (see Fig. 3 for the sample size of 8, which is the number of datasets attributed to the warm ENSO events that occurred during the period of analysis of 1950-1998). A confidence level γ indicates that (1-γ)100% of the variability is attributable to random variability. Fortran routines provided in Numerical Recipes (Press et al., 1992) are used to compute the confidence intervals. Before applying the test, we normalised the data and also demonstrated the possible loss of power of the t-test as a result of the small sample size considered as shown in Fig. 3 for a sample size of 8, 16 and 32.

Results and discussion

A correlation coefficient between seasonal warm ENSO indices and annual discharge of a typical river in Malawi over 8 consecutive quarters is shown in Table 2. It shows that the mean annual discharge of the river considered is positively correlated with the four quarter SLPs observed during the El Niño years. Amongst the 8 quarters, a strong positive correlation (r>0.52) between annual discharges seems to be apparent in the rainy season DJF quarter. The confidence level of the correlation coefficient for quarter DJF is about 80% (Fig. 3). The positive correlation diminishes for the other seasonal quarters, and the correlation becomes negative in the quarters that precede and follow the El Niño years. For this reason, we studied the correlation between the DJF quarter warm ENSO indices and annual discharge of the rivers.

Figure 4 shows the correlation between the annual discharge of the 502 rivers considered across the Southern African region and the three-month mean warm ENSO indices of December to February (DJF). In Fig. 4 the correlation coefficients are marked at the locations of the discharge gauging stations. Figure 5 is a summary of the correlation coefficient for the 502 rivers.

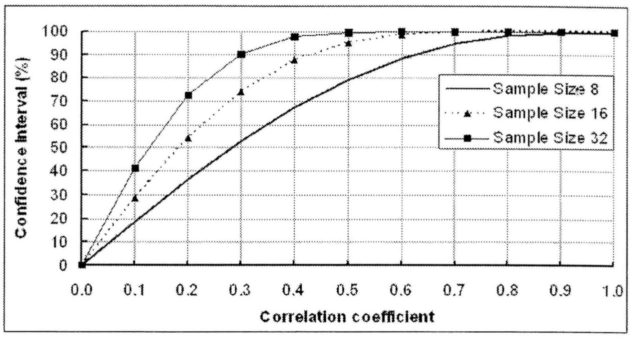

Figure 3
Relation of the correlation coefficients and the confidence intervals used in the study

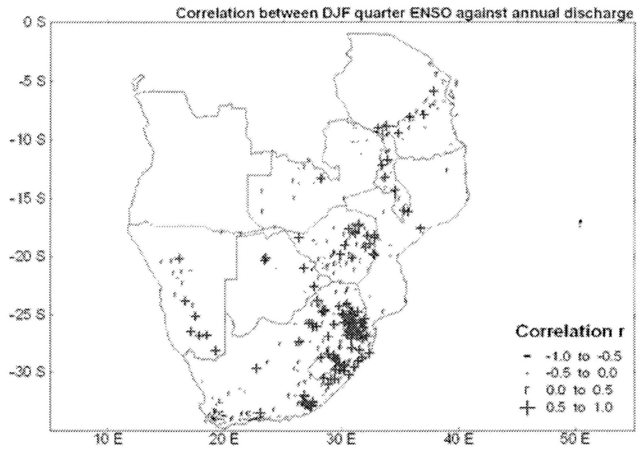

Figure 4
Correlation between the annual discharge of the 502 rivers considered and the December to February (DJF) mean ENSO in the region of Southern Africa

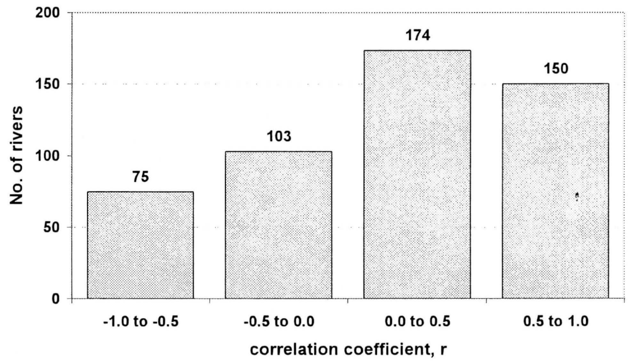

Figure 5
Summary of coefficients of correlation between December to February ENSO and mean annual discharge of 502 rivers in Southern Africa during El Niño years of 1950-1998

Work	Who
Although the rough outline of the basin is defined, it needs to be refined	Stakeholders
Refine using new outline	Ngula/Carole
Refine using new outline	Ngula/Carole
Make an image of the area	Ngula
Update some of the layers and put together as a detailed map of the area	Carole/Ngula
Cut out with refined basin outline	
Using Atlas and topo maps label on map	
To be included on orientation map	
To be included on orientation map	
To be included on orientation map	
To be included on orientation map	
To be included on orientation map	
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To be included on orientation map	
	Carole/Ngula
Agmet data plus updates on more long-term stations; commercial farmers; mines; big towns; chat to John Irish	
Calculated from monthly totals	
Calculated from monthly totals	
Calculated from monthly totals	
Calculated from monthly totals	
Daily rainfall figures required to match up with river flow and look at episodic events	
Adapt from the Atlas to include winter rainfall	
Oranjemund and Luederitz	
Wind regimes at coast and inland	
Temperature regimes at coast and inland	
Temperature regimes at coast and inland	
Temperature regimes at coast and inland	
Temperature regimes at coast and inland	

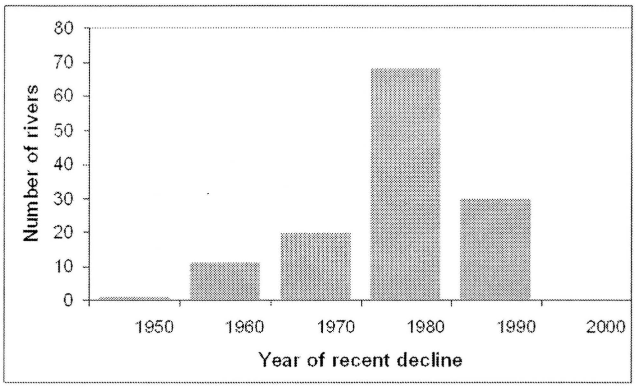

Figure 6
The frequency of rivers and the year of recent significant decline in the annual discharge of 130 rivers in the Southern African region [source: Alemaw et al., 2001]

In general, during El Niño years, of the 502 rivers we considered positive correlation prevails in 324 rivers (i.e. 65%). The variability in the annual flow of 150 rivers is strongly positively correlated (0.5 to 1.0) with the DJF ENSO index during the 8 El Niño years considered – with more than 25% of the variance in annual discharge being accounted for by the El Niño event. During the same rainy season (DJF quarter), smaller but positive correlation (0 to 0.5) occurred in the 174 rivers. During the same season negative correlations (0 to -0.5) and (-0.5 to -1.0) are prevalent in 103 and 75 rivers, respectively, which account for 35% of the rivers we considered.

The positive correlation between warm ENSO phenomena in some parts of Southern Africa is an indication of the decline in river runoff associated with the corresponding below-normal rainy season rainfall in the region during El Niño years. Similar findings of the occurrence of below-normal rainfall amounts from December to March during El Niño years have been noted in South Africa (Landman and Klopper, 1998). Noting the warm ENSO positive association with drier rainfall conditions in Southern Africa (Ropelewski and Halpert, 1987), this study further reveals evidence of possible below-normal discharge or discharge reductions during El Niño years.

Long-term trends in warm ENSO and river flow

A number of climate indicators are noted to have changed in 1976, especially around the Pacific Basin. As can be seen on Fig. 2, before the mid-1970s El Niño seems to have occurred with about equal frequency, each at intervals of about 3 to 7 years, and between 1976 and 1995 alone, there have been about 9 El Niños (using a 6-month average of the Southern Oscillation Index of -0.50 as the criteria, or one every 2.2 years). There has been just one moderate La Niña in that interval (1988-89) and a rather weak La Niña (not even counted by some) in 1996-97. Longer perspectives, since 1860, indicate that the 1976-1997 period is quite unlike any other in the record. This is a source of considerable puzzlement at this time.

This analysis of the long-term trend of the El Niño phenomenon over the period 1950 to 1998, depicted in Fig. 2, supports the findings of decline in river runoff of several rivers in Southern Africa (Alemaw and Chaoka, 2002; Alemaw et al., 2001). The authors used the automatic series segmentation technique of Hubert (1989; 1997), followed by the split-sample test of two sample mean differences at a significance level of 5%. Of the 502 rivers considered, a statistically significant decline in the annual river runoff is reported in 130 rivers. The histogram of decline periods identified in the aforementioned study is shown in Fig. 6. Most of the decline occurred since the mid 1970s. The rivers where decline prevailed are found in the southern parts of Zambia, Namibia, Mozambique and the lowveld in South Africa as provided in Alemaw et al. (2001). The decline in the flow of the majority of the rivers since the 1970s (Fig. 6) can possibly be a mere reflection of the effect of the long-term trend of El Niño phenomena.

Conclusions

This study revealed that a strong positive correlation exists between the 1950-1998 warm ENSO indices (explained by the SLP anomalies) and annual discharge of the 502 rivers in the Southern African region. We have also found during the El Niño years that a significant variance of the annual flow regime is accounted for by the El Niño phenomenon. The correlation is strong (r>0.5) in 150 rivers during the rainy season of December to February (DJF), with confidence intervals reaching above 80%. It signifies the possible association of year-to-year variability of river runoff with El Niño phenomena, the latter accounting for over 25% of the variability of the former. Positive correlations of less than 0.5 are evident in 174 rivers. On the other hand, in the long-term sense, more frequent El Niño episodes have occurred since the mid-1970s than before (Fig. 3) that imply a strong implication of recent recurrent droughts during this period.

The recent recurrent decline of river runoff, predominantly in the mid- 1970s, in the river flow regimes of Southern Africa seems to be associated with the same period prevalence of the high frequency of drought-related ENSO phenomena. The correlation between ENSO phenomenon and discharge of rivers in the Southern African region further confirms that the El Niño phenomenon is one of the major contributors in the year-to-year natural variability of runoff in the region.

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Best Practices

Nico Noord
Aussenkehr?
Some of the small rural projects learnt in PPA?
Some of the large organisations – eg. mines?
Gondwana
Salt block health problems

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Erb – Data needs for profile

Subject	Source
Definition of the Basin	DRWS
Boundaries and neighbouring basins	DRWS
Landscapes/landforms	Atlas
Altitudinal profiles?	
Satellite image of area	Landsat/Tiger
Detailed topographical map	Atlas
altitude	Atlas?
mountains	Atlas + topo maps of the area
spot heights	?
features of interest	Topo and other recent maps
rivers	hydrogeological map / Atlas
pans	hydrogeological map / Atlas
dams	Atlas
protected areas	Atlas / Coninfo for new areas
conservancies	Atlas / Coninfo for new areas
political and administrative boundaries	Atlas
infrastructure	
roads	Atlas / Coninfo for new areas
powerlines	Atlas / Nampower
airstrips	Atlas / Aviation
education facilities	Atlas / EMIS
health facilities	Atlas / MoHSS
police	Atlas / Ministry of Security
border posts	Atlas / Ministry of Home Affairs
railways	Atlas
mines	Atlas / Geological Survey
Climate	
Rainfall	Agmet data / weather bureau / private
Monthly and annual averages/medians	
Total figures	
Variation	
Long-term	
Event data	Commercial farmers / weather bureau
Systems	
Winter	
Summer	
Fog	Weather bureau
Wind	Weather bureau
Solar radiation	Weather bureau
Temperatures	Weather bureau
Annual average	Weather bureau
Average minimum	Weather bureau