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Drivers of spatial and temporal variability of streamflow in the Incomati River Basin

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Abstract

The Incomati is a semi-arid trans-boundary river basin in southern Africa, with a high variability of streamflow and competing water demands from irrigated agriculture, energy, forestry and industries. These sectors compete with environmental flows and basic human water needs, resulting in a "stressed" water resources system. The impacts of these demands, relative to the natural flow regime, appear significant. However, despite being a relatively well-gauged basin in South Africa, the natural flow regime and its spatial and temporal variability are poorly understood and remain poorly described, resulting in a limited knowledge base for water resources planning and management decisions. Thus, there is an opportunity to improve water management, if it can be underpinned by a better scientific understanding of the drivers of streamflow availability and variability in the catchment.

In this study, long-term rainfall and streamflow records were analysed. Statistical analysis, using annual anomalies, was conducted on 20 rainfall stations, for the period of 1950 to 2011. The Spearman Test was used to identify any trends in the records at annual and monthly time scales. The variability of rainfall across the basin was confirmed to be high, both intra- and inter-annually. The statistical analysis of rainfall data revealed no significant trend of increase or decrease for the studied period. Observed flow data from 33 gauges was screened and analyzed, using the Indicators of Hydrologic Alteration (IHA) approach. Long-term analyses were conducted to identify temporal/spatial variability and trends in streamflow records. Temporal variability was high, with the coefficient of variation of annual flows in the range of 1 to 3.6. Significant declining trends in October flows, and low flows indicators were also identified at most gauging stations of the Komati and Crocodile sub-catchments, however no trends were evident on the other parameters, including high flows. The trends were mapped, using GIS and were compared to historical and current land use. These results suggest that land use and flow regulation are larger drivers of temporal changes

in the streamflow than climatic forces. Indeed, over the past 40 years, the areas under commercial forestry and irrigated agriculture have increased over four times.

1 Introduction

Global changes, such as climate change, population growth, urbanization, industrial development and the expansion of agriculture, put huge pressure on natural resources, particularly water (Miao et al., 2012; Milly et al., 2008; Jewitt, 2006a; Vörösmarty et al., 2010; Montanari et al., 2013). In order to manage water in a sustainable manner, it is important to have a sound understanding of the processes that control its existence, the variability in time and space and our ability to quantify that variability (Jewitt et al., 2004; Hu et al., 2011; Hughes et al., 2014; Montanari et al., 2013).

Water is critically important to the economies and social well-being of the predominantly rural populations within southern Africa, where environmental sustainability issues are increasingly coming into conflict with human development objectives and where data are also scarce. The local economies and livelihoods of many southern African communities are strongly dependent on rain-fed, or irrigated, agriculture and fisheries, and water availability remains one of the main constraints to development in Africa (Jewitt, 2006a; Pollard and du Toit, 2009). Hydro-power is also locally important, while a substantial amount of foreign income is derived from wildlife tourism in some countries of the region (Hughes et al., 2014).

Climate change intensifies the global hydrological cycle, leading to more frequent and variable extremes. For southern Africa, recent studies forecast an increase in the occurrence of drought due to decreased rainfall events (Lennard et al., 2013; Shongwe et al., 2009; Rouault et al., 2010). Furthermore, it is expected that temperatures will rise, and thus the hydrological processes driven by temperature will intensify (Kruger and Shongwe, 2004; Schulze, 2011). Compounding the effect of climate change are the increased pressures on land and water use, owing to increased population and the consequent requirements for food, fuel and fibre (Rockström et al., 2009; Warburton et al., 2012, 2010). Areas of irrigated agriculture and forestry have been expanding steadily over the past decades. Urbanization also brings with it an increase in impervious areas and the increased abstraction of water for domestic, municipal and industrial purposes (Schulze, 2011).

In southern Africa, these pressures have led to dramatic changes in natural streamflow patterns. However, not many studies are available concerning the magnitude of such changes and what the main drivers are (Hughes et al., 2014). Projections on the impact of climate change on the water resources of South Africa were investigated by Schulze (2012) and some research has been done (Love et al., 2010; Fanta et al., 2001), analysing streamflow trends in other southern Africa rivers, but no such studies are available for the Incomati Basin.

The Incomati is a semi-arid trans-boundary river basin in southern Africa, which is water-stressed because of high competing demands from, amongst others, irrigated agriculture, forestry, energy, environmental flow and basic human needs provision (DWAF, 2009d; TPTC, 2011). The impact of these demands, relative to the natural flow regime, is significant. Hence, there is an opportunity to improve water management, if a better scientific understanding of water resources availability and variability can be provided (Jewitt, 2006a).

The goal of this paper is to determine whether or not there have been significant changes in rainfall and streamflow dynamics during the time of record, and what the potential reasons and implications of such changes are. The main research questions are:

- Does the analysis of precipitation and streamflow records reveal any persistent trends?
- What are the drivers of these trends?
- What are the implications of these trends for water management?

The variability and changes of rainfall and streamflow records were analysed and the possible drivers of changes were identified from the literature, as well as from the further analysis of the water resources assessment reports previously conducted in the area. The spatial variation of trends on streamflow and their possible linkages with the main drivers are analysed. Based on the findings, approaches and alternatives for improved water resources management and planning are proposed.

2 Methodology

2.1 Study area

The Incomati River Basin is located in the south-eastern part of Africa and it is shared by the Kingdom of Swaziland, the Republic of Mozambique and the Republic of South Africa (Fig. 1). The total basin area is approximately 46 750 km^2, of which 2 560 km^2 (5.5 %) is in Swaziland, 15 510 km^2 (33.2 %) in Mozambique and 28 681 km^2 (61.4 %) in South Africa. The Incomati watercourse includes the Komati, Crocodile, Sabie, Massintonto, Uanetze and Mazimechopes Rivers and the estuary (TPTC, 2011). The Komati, Crocodile and Sabie are the main sub-catchments, contributing about 94 % of the natural discharge, with an area of 61 % of the basin. The Incomati River rises in the mountains (2000 m a.s.l.) in the west of the basin and drops to the coastal plain in Mozambique. The general climate in the Incomati River Basin is semi-arid, and varies from a warm to a hot humid climate in Mozambique to a cooler dry climate in South Africa in the west. The mean annual precipitation of about 740 mm a^{-1} falls entirely during the summer months (October to March). The Incomati (see Fig. 1) can be topographically and climatically divided into three areas (TPTC, 2011):

- High-lying escarpment, with a relatively high rainfall (800 to 1600 mm a^{-1}), low temperatures (mean annual average of 10 to 16 °C) and lower potential evaporation (1600 to 2000 mm a^{-1});
- Highveld and middle Lowveld, which lies between the Drakensberg and the Lebombo Mountains, warmer than the escarpment (mean annual average of 14

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to 22 °C), with rainfall that reduces towards the east (400 to 800 mm a^{-1}) and high potential evaporation (2000 to 2200 mm a^{-1});

– Coastal plain, located mostly in Mozambique, with relatively higher temperatures (mean annual average of 20 to 26 °C) and lower rainfall (400 to 800 mm a^{-1}) in the west, increasing eastward towards the coast, where there is also high potential evaporation (2200 to 2400 mm a^{-1}).

The complex geology of the basin is characterized by sedimentary, volcanic, granitic and dolomitic rocks, as well as quaternary and recent deposits (Van der Zaag and Vaz, 2003). The soils in the basin are highly variable, ranging from moderately deep clayey loam in the west, to moderately deep sandy loam in the central areas and moderately deep clayey soils in the east. The dominant land uses in the catchment are commercial forestry (pine, eucalyptus) in the escarpment region, dryland crops (maize) and grazing in the Highveld region and irrigated agriculture (sugarcane, vegetables and citrus) in the Lowveld (DWAF, 2009d; Riddell et al., 2013). In the Mozambican coastal plains, sugarcane and subsistence farming dominate. A substantial part of the basin has been declared a conservation area, which includes the Kruger National Park and the recently established Great Limpopo Transfrontier Park (TPTC, 2011).

The level of water abstraction in the Incomati River is very high and the actual water demand is projected to increase in the future, as a result of further economic development and population growth (Nkomo and van der Zaag, 2004; LeMarie et al., 2006; Pollard et al., 2011). The consumptive use of surface water amounts to more than 1880 million cubic metres per annum (10^6 m^3 a^{-1}), which represents 51 % of the average amount of surface water generated in the basin (Van der Zaag and Vaz, 2003). The major water consumers (see Tables 1 and 2), accounting for 91 % of all consumptive water uses, are the irrigation and forestry sectors, followed by inter-basin water transfers to the Umbeluzi Basin and the Olifants Catchment in the Limpopo Basin (TPTC, 2011; DWAF, 2009d; Van der Zaag and Vaz, 2003). Since 1950s the area of irrigated

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agriculture and forestry has increased steadily, particularly in the Komati and Crocodile systems, as can be seen on Table 2.

2.2 Data and analysis

2.2.1 Rainfall

Rainfall data of the annual, monthly and daily rainfall for Southern Africa for the period of 1905 to 2000 was extracted from the Lynch (2003) database. The database consists of daily precipitation records for over 12 000 stations in Southern Africa, and data quality was checked and some data was patched. The main custodians of the rainfall data are SAWS (South Africa Weather Service), SASRI (South Africa Sugarcane Research Institute) and ISCW (Institute for Soil Climate and Water). About 20 stations out of 374 available for Incomati, with the best quality data (evaluated by the percentage of reliable data indicated on the database) and the representative spatial coverage of the basin were selected for detailed analysis. The percentage of reliability represents the percentage of good observed data over the entire time series. Eight of the 20 time series were extended up to 2012, using new data collected from the SAWS.

The spatial and temporal heterogeneity in rainfall across the study area was characterised using statistical analysis and annual anomalies. The time series of annual and monthly rainfall from each station was subjected to the Spearman Test (McCuen, 2003), in order to identify any trends for the period of 1950–2000 and 1950–2011. The Pettitt Test (Pettitt, 1979) was also used, to detect abrupt changes in hydrological series. The test determines the timing of a change in the distribution of a time series, known as a "change point" (Love et al., 2010; 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. A probability threshold of 0.8 was used for the Pettitt test to identify the change points, followed by F and T tests at 95 % confidence level. The annual and monthly time series were also

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analysed for the presence of serial correlation. Tests were carried out using SPELL-stat v.1.5.1.0B (Guzman and Chu, 2004).

2.2.2 Streamflow

In the Incomati Basin, DWA (Department of Water Affairs) is the custodian of 104 gauging stations in South Africa. In Mozambique, ARA-Sul is the custodian of gauging stations and flow data from two gauges was acquired for this study. The discharge data from the gauging stations from the DWA database, with time-series lengths ranging from 1909 to 2012, was collected and screened. Based on the quality of data, time series length, influence of infrastructure (dams, canals) and spatial distribution, 33 stations were selected for detailed analysis (see Table 3 and Fig. 2). As this catchment is highly modified, very few stations could be considered least impacted by human interventions. An analysis of the 33 indicators of hydrologic alteration was conducted (Richter and Thomas, 2007; Richter et al., 1996, 2003) and summarized, to identify patterns and trends of the streamflow record (a single period analysis for the entire time series and for the period of 1970–2011), as well as to assess the impact of infrastructure on the streamflow (two-period analysis, before and after the major infrastructure development).

2.2.3 Indicators of Hydrologic Alteration

The US Nature Conservancy developed a statistical method known as the "Indicators of Hydrologic Alteration" (IHA), for assessing the degree to which human activities have changed flow regimes. The IHA method (Richter and Thomas, 2007; Richter et al., 1996, 2003) is based upon the concept that hydrologic regimes can be characterized by five ecologically-relevant attributes: (1) magnitude of monthly flow conditions, (2) magnitude and duration of extreme flow events (e.g. high and low flows), (3) the timing of extreme flow events, (4) frequency and duration of high low flow pulses, and (5) the rate and frequency of changes in flows.

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Table 4 shows the hydrological parameters analysed within each indicator group. Analyses are based on availability of daily flow data, so selected gauges from the Incomati Basin were analysed with this method. Many studies successfully applied the methodology of "Indicators of Hydrologic Alteration", in order to access impacts on streamflow caused by anthropogenic drivers (Taylor et al., 2003; Mathews and Richter, 2007; Maingi and Marsh, 2002; De Winnaar and Jewitt, 2010; Masih et al., 2011). In the case of the present study, the indicators of magnitude of monthly water conditions, magnitude and duration of extreme water conditions, as well as timing were analysed in the same period (1970–2011), to assess whether consistent trends of increase or decrease of the flow metrics were present.

The IHA software was used to identify linear trends of the streamflow time series, based on the regression of least squares. This trend is evaluated with the P value, and only trends with $P \leq 0.05$ were considered significant trends. The value of the slope of the trend line indicated whether the trend was increasing or decreasing. This information was compiled for the various hydrological indicators and plotted spatially, using ArcGIS 9.3.

2.2.4 Land use analysis

Land use analysis was conducted, based on secondary data, as remote sensing maps are available only from a period when most of the current forestry plantations were already established. Additionally, a map of current land use (2011) and land use of 2004 were compared with the maps of trends of indicators of hydrologic alteration. Where the occurrence of trends in flow regime was consistent with the changes in land use, this was further investigated, by looking at temporal evolution on the land use change.

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3 Results

3.1 Rainfall

Statistical analysis was conducted on the 20 rainfall stations described in Table 5, for the period of 1950 to 2011. The variability of rainfall across the basin was confirmed to be high, both intra- and inter-annually, with a wide range between years. It is interesting to note that this variability is higher for the stations located on the mountainous areas, due to the elevation gradient. The variability across the basin is also significant, as illustrated by the box plot of Fig. 3.

The investigation of trends on the annual time series revealed no significant trends on most stations using the Spearman Trend Test, at 95 % confidence level. Only 5 of the 20 investigated stations showed significant trends of increase (2 stations) and decrease (3 stations). However, the stations that presented significant trends are also stations with low percentage of reliability, thus it is possible that the trend identified could be affected by data infilling procedures. The existence of a serial correlation on annual and monthly time series was also investigated, but was not found to be present. Some change points were identified using the Pettitt Test, mostly on the years 1978 and 1971 (Table 5). The significance of the change was assessed with T test and F test in the change of mean and the variance of the sub-series obtained from the change points, at 95 % confidence level. Only 2 stations out of the twenty studied showed significant change towards a wetter regime (Riverbank and Manhica).

Figure 4 shows, for example, the anomalies of annual rainfall and the moving average for the stations of Machadodorp and Alkmaar. Monthly rainfall also does not exhibit any clear trend of an increase or decrease in most of the stations. This is consistent with the larger scale analyses conducted by Schulze (2012) for South Africa and Shongwe et al. (2009) for Southern Africa.

Mussá et al. (2013) studied the trends of annual and dry extreme rainfall, using the Standardized Precipitation Index (SPI) and also found no significant trends on the annual rainfall precipitation extremes across the Crocodile sub-catchment.

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3.2 Variability of streamflow

The metrics of the different hydrologic indicators were compiled as an output of the IHA analysis. The results for the gauging stations located at the outlet (or the most downstream) of each main sub-catchment are presented in Table 6, as an example. The variability is described, using non-parametric statistics (median and coefficient of dispersion), because the hydrological time series are not normally distributed, but positively skewed. The coefficient of dispersion (CD) is defined as CD = (75th percentile – 25th percentile)/50th percentile. The higher the CD, the higher the variation of the parameter will be.

The flow patterns are consistent with the summer rainfall regime, with highest flow and rainfall events associated with tropical cyclone activity in January–March.

A comparison of the flow normalized by area (Fig. 5) for the main sub-catchments reveals that Sabie yields a higher runoff than Komati and Crocodile. This is the case because the observed streamflows include the impact of water abstractions and streamflow reduction activities, which are more intense in the Komati and Crocodile sub-catchments (Mallory and Hughes, 2012; Hughes and Mallory, 2008).

Another aspect to note is that the flows of February are likely to be higher than observed records, but are buffered due to flow regulation, or because high streamflow extremes are not fully captured by the current monitoring network.

3.3 Trends in streamflow

In Fig. 6, the plot of trends indicated by the slope of the trend line is presented per selected hydrological indicator. For comparison, the same indicators are plotted for the periods 1970–2011 (Fig. 6a) and for 1950–2011 (Fig. 6b). The significant trends are highlighted with a circle. Table 7 presents the slope of the trend lines and *P* values for the gauges located at the outlet, or the most downstream point of each main sub-catchment. The first observation is a significant trend of decreasing mean flow in October in almost all stations, especially the ones located on the main stem of the

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Crocodile and the Komati. This means that along the entire basin the month of October is when more water stress is experienced, which is explained by the fact that this is the month of the start of the rainy season, when the dam levels are lowest and irrigation water requirements are highest (DWAF, 2009c; ICMA, 2010).

This trend is consistent with the decreasing trends of minimum flows, as exemplified by the 7 day minimum. In contrast, it can be seen that the count of low pulses increased significantly in many gauges, which indicates the more frequent occurrence of low flows. Another striking trend is the significant increase of the number of reversals of almost all stations, indicating the effect of flow regulation and water abstractions (reversals occur when an increasing flow rate changes to a decreasing flow rate).

The significant trends (95 % confidence level) occurring on the various indicators were counted per station and plotted on the map in Fig. 7. The salient pattern on the map is that more significant decreasing trends occur in the Komati and Crocodile systems, which are also the most stressed sub-catchments. Another interesting aspect is that some of the trends cross-compensate each other. Some of the positive trends occurring on the tributaries of the Crocodile, for example, the October Median Flow and baseflow are cancelled as we move downstream the main stem.

The cross-compensation can also be observed at basin-scale on the Sabie, where the trends of decreasing flows are not so frequent or significant. It is likely that this occurs because the majority of the Sabie falls under the conservation area of the Kruger National Park (KNP) and therefore no major abstractions occur here. The KNP has been playing an important role in the catchment management fora set up by the ICMA, which concern the provision of environmental minimum flows, in order to ensure the maintenance of ecosystem and biodiversity in the Park (Pollard et al., 2012; Riddell et al., 2013).

Table 7 illustrates that many of the trends observed in the Sabie sub-catchment are contrary to those observed in the Komati and Crocodile sub-catchments. Thus, it is likely that the trends observed in downstream E43 - Magude, in Mozambique, are as

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a result of a combination of the positive effect of the conservation approach of KNP on the Sabie, and the negative effect of flow reductions in the Crocodile and the Komati.

From Table 7 and Fig. 7, it can be seen that the Komati sub-catchment (at Tonga Gauge, X1H003) is where most negative trends occur, particularly significant during the months of October, June and July. In the Crocodile (at Tenbosch Gauge, X2H016) the trends are not visible, because a lot of cross-compensations have already occurred. The Kaap and Elands tributaries of the Crocodile River have significant decreasing trends on their mean monthly flows, as well as on the low flows. On the other hand, the Kwena Dam, which is located on the main stem of the Crocodile, is managed in a way to augment the flows during the dry season. This results in increasing flows during the low flow months.

It is important to note that these trends are even more pronounced, when longer time series are considered. Two examples from the Crocodile Basin are presented below.

3.3.1 Example of decreasing trends: Noord Kaap X2H010

The Noord Kaap Gauge (X2H010), located on a tributary of the Crocodile sub-catchment showed the most intriguing trends. Out of the 33 indicators (IHA), this gauge had 12 significant trends, 10 of them negative, which indicate a major shift in flow regime over the period of analysis. However, there is no record of a dam or major infrastructure being constructed (DWAF, 2009b). The records of nearby rainfall station of Kaapsehoop (0518455W) does not show a significant trend of decrease of rainfall, which suggests the reduction observed in streamflow could be a result of land use change, namely, conversion to forestry and irrigated land. The decreasing trends occur in all months, but are more pronounced during low flow months, particularly September (Fig. 9) and October. There is a significant decrease of high flows and small floods and an increase of extreme low flows. The annual flow duration curve for the periods 1949–1974 and 1978–2011 shows a dramatic decrease in annual flows. Figure 10 illustrates the comparison of median monthly flows for the two periods. From the analysis of land use changes over time (Table 2), it can be seen that the sharp decrease

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of mean monthly flows during the 1960s coincides with an increase of the area under irrigated agriculture. During the 1970s there was also a great increase of area under forestry, namely, Eucalyptus (DWAF, 2009c). Commercial forestry consumes more water through evaporation than the native vegetation it replaces, therefore, under the South African National Water Act, commercial forestry must be licensed as a water user, which is termed a Streamflow Reduction Activity (SFRA) (Jewitt, 2002, 2006b).

3.3.2 Impact of the Kwena Dam on streamflows of the Crocodile River

The Kwena Dam is the main reservoir on the Crocodile system, located upstream in the catchment, commissioned in 1984. The dam is used to improve the assurance of supply of water for irrigation purposes in the catchment. The Montrose Gauge (X2H013) is located few a kilometres downstream of this dam. The two-period (1959–1984 and 1986–2011) analyses illustrated the main impacts of Kwena Dam on the river flow regime, which are reversed seasonality, the dampening of peak flows and an increase on low flow and base flow indices. These results are consistent with the analysis conducted by Riddell et al. (2013), which found significant alterations of natural flow regime in the Crocodile Basin over the past 40 years. They developed a methodology to assess historical compliance with environmental water allocations, and reported that there is a high incidence of non-compliance, reduction of low flows and some homogenisation of the flow regime, as a result of dam operation. Similar impacts were found in studies in different parts of the world (Maingi and Marsh, 2002; Richter et al., 1998; Bunn and Arthington, 2002; Birkel et al., 2014).

It can be seen that this reservoir is managed to augment the low flows and attenuate floods. This change in the flow regime influences the streamflow along the main stem of the Crocodile River, but as tributaries join it, and water is abstracted, the effect is reduced. At the outlet in Tenbosch, X2H016 (Fig. 7 and Table 7), the effects of flow regulation and water abstractions have already counter-balanced the contrasting trends observed upstream.

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3.3.3 Impact of anthropogenic actions

As can be seen from water use information, the impacts of land use change, reservoir operation and water abstractions are the main drivers of changes in the flow regime on the Incomati. However, the situation is variable along the catchment. In the Sabie system, in spite of great areas of commercial forestry in the headwaters, the indicators of mean, annual and low flows do not show significant trends (see Table 7). This can be explained by the fact that most of the forestry area was already established during the period of analysis for trends (1970–2011) (DWAF, 2009a). The fact that a large proportion of the Sabie sub-catchment is under conservation land use (KNP and other game reserves) also plays an important role in maintaining the natural flow regime.

On the Crocodile, however, irrigated agriculture, forestry and urbanization were the most important anthropogenic drivers. They affect the streamflow regime, the water quantity and possibly the water quality as well (beyond the scope of this analysis). This has important implications when environmental flow requirements and minimum cross-border flows need to be adhered to. Pollard and du Toit (2011a) and Riddell et al. (2013) have demonstrated that the Crocodile River is not complying to environmental flow requirements during most of the dry season at the outlet.

On the Komati, the strategic water uses, which have first priority (such as water transfer to ESKOM plants in the Olifants Catchment and to irrigation in the Umbeluzi) (Nkomo and van der Zaag, 2004; DWAF, 2009d), have a high impact on streamflows. Because of other water allocations, for irrigation, forestry and other industries, steady trends of decreasing flows could be identified. This is another system where the environmental flows and cross-border requirements are often not met during the dry season (Pollard and du Toit, 2011a; Riddell et al., 2013; Mukororira, 2012).

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4 Discussion

4.1 Limitations of this study

The available data series had some gaps, especially during high flow periods. Because of this, the analysis of high flow extremes is highly uncertain. For the trend analysis, the period of common data followed the construction of a lot of impoundments and other developments.

Another challenge is the disparity of data availability across the different riparian countries. In Mozambique, only two gauges had reliable flow data for this analysis, representing the entire Lower Incomati system. The rivers Massintonto, Uanetze and Mazimechopes, in Mozambique do not have active flow gauges. There is definitely a need to strengthen the hydrometric monitoring network in the Mozambican part of the basin, as well as on the tributaries originating in the Kruger National Park.

Some gauges are from nested catchments. A lot of trends and alterations counterbalance each other, as can be seen clearly in the Crocodile system. However, some cases of contradictory trends that occurred could possibly be explained by the change of measurement equipment and the adjustment of the flow rating curves. An analysis of the best quality stations and a number of stations in the same system was conducted, to avoid this pitfall.

4.2 What are the most striking trends and where do they occur?

The analysis resulted in the identification of major trends, such as:

- Decreasing trends of the magnitude of monthly flow (significant for low flow months, e.g. October), minimum flow (1, 3, 7, 30 and 90 day minimum) and the occurrence of high flow pulses;

– Significant increasing trends of the magnitude of monthly flow (August and September) in some locations in the Crocodile and Sabie, and on the occurrence of flow reversals basin wide;

– Some gauges showed no significant change or no clear pattern of change on the parameters analyzed. These are mainly gauges located on the Sabie, which by 1970 had established the current land use seen to the present day.

In the Komati system, the flow regulation and water abstractions have very strong impacts on streamflow. Most gauges are already severely impacted and it is quite difficult to characterize natural flow conditions. Flow regulation has highest impact on low flow and minimum flows. In the Komati, there is significant irrigated agriculture, particularly sugar-cane. The upstream dams of Nooitgedacht and Vygeboom are also mainly used to supply cooling water to ESKOM power stations outside the basin; thus, the water is exported and not used within the basin.

In the Crocodile system the flow regulation, through the operation of the Kwena Dam, for example, has impacted on the attenuation of extreme flow events. The high flows are reduced and the low flows generally increase, leading to reverse seasonality downstream of the Kwena Dam. The dam is used to improve the assurance of the supply of water for irrigation purposes in the catchment. However, on X2H010 – Noord Kaap, a headwater tributary of the Crocodile, there is a significant and dramatic reduction of flows, shown in the monthly flow, the flow duration curves and the low flow parameters. This change is compared, by inference, using land use data, with the increase in the area under forestry in the sub-catchment, as well as with the increase in irrigation.

In the Sabie system, most gauges did not show varied significant trends. This is most likely due to fewer disturbances: lower water demands, less water abstractions and larger areas under conservation. During the period from 1970 to 2011, there were no clear impacts of climatic change (in terms of rainfall) on the streamflow.

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4.3 Implications of this findings for water resources management

When the analysis of trends is combined with the land use of the basin (Fig. 8), it is clear that the majority of gauges with decreasing trends are located in areas were forestry or irrigated agriculture dominate the land use and where conservation approaches are less prevalent. The presence of water management infrastructure (dams) highly influence the flow regime.

For the management of water resources in the basin, it is important to note that there are some clear patterns illustrated by the Sabie, Crocodile and Komati. The Sabie flows generated in the upper parts of the catchment persist, whilst in other rivers, where the Kruger National Park or the Catchment Management Agency Forum is less of an influence, flows are highly modified. This suggests that the use of the conservation approach through the Strategic Adaptive Management of the KNP and ICMA can be very beneficial to keep environmental flows in the system. It is important to consider not only the magnitude of flows, but their duration and timing as well.

To some extent, dams do provide storage and attenuate floods in the basin, but have impacts downstream, such us the change of mean monthly flows and reverse seasonality, which can hamper the health of ecosystems downstream of the dams. So other possibilities of water storage should be further investigated and adopted in the basin in future, such as aquifer storage, artificial recharge, rainfall harvesting, etc. The design of operation rules for dams should also aim at mimicking the system's natural variability.

Given the likely expansion of water demands, due to urbanization and industrial development, it is also important that water demand management and water conservation measures are better implemented in the basin. For example, there could be systems to reward users that use technology to improve their water use efficiency and to municipalities that encourage their users to have lower water demands.

This study also shows the complexity of water resource availability and variability. This is even more relevant, considering that this is a transboundary basin and that

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there are international agreements regarding minimum cross-border flows and maximum development levels that have to be adhered to (Pollard and Toit, 2011a, b; Nkomo and van der Zaag, 2004; Riddell et al., 2013).

There is a great discrepancy of data availability between different riparian countries. It is very important that Mozambique, in particular, improves its monitoring network, in order to better assess the impact of various management activities occurring upstream on the state of water resources. The monitoring of hydrological extremes should receive more attention, with focus on increasing the accuracy of recording the flood events.

5 Conclusions

The research conducted shows important interactions of the dynamics of streamflow that are complex and intertwined, often working simultaneously within a river basin.

The statistical analysis of rainfall data revealed no consistent significant trend of increase or decrease for the studied period. The analysis of streamflow, on the other end, revealed significant decreasing trends of streamflow indicators, particularly the median monthly flows of September and October, and low flow indicators. This study concludes that land use and flow regulation are larger drivers of trends in the streamflow in the basin. Indeed, over the past 40 years the areas under commercial forestry and irrigated agriculture have increased over four times, increasing the water use, basin wide.

The study therefore recommends that conservation approaches to water management, such as strategic adaptive management adopted by the Kruger National Park and Inkomati Catchment Management Agency, should be further deployed in the basin. Water demand management and water conservation should be alternative options to the development of dams, and should be further investigated and established in the basin. Land use practices, particularly forestry and agriculture, have a significant impact on water quantity of the basin; therefore, stakeholders from these sectors should work closely with the water management institutions, to keep flow regime close to the natural variability.

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Considering the high spatial variability in the observed changes, no unified approach will work, but the specific interventions for the most affected sub-catchments and main catchments. Future investigations should conduct a careful assessment of benefits derived from water use should be done, in order to assess if the first priority water uses are indeed the most beneficial; this should be done basin wide.

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Table 1. Summary of estimated natural streamflow, water demands in the Incomati Basin in 10^6 m^3 year^{-1} (TPTC, 2011) and major dams (> 10^6 m^3) (Van der Zaag and Vaz, 2003).

	Natural MAR	First Priority Supplies	Irrigation Supplies	Afforestration	Total Water Use
Komati	1332	141.5	621	117	879.5
Crocodile	1124	74.7	482	158	714.7
Sabie	668	30	98	90	218
Massintoto	41	0.3	0	0	0.3
Uanetse	33	0.3	0	0	0.3
Mazimechopes	20	0	0	0	0
Lower Incomati	258	1.5	412.8	0	414.3
Mozambique	325		412.8		
South Africa	2663		961		
Swaziland	488		240		
Total	3476	248	1614	365	2227

Tributary	Country	Major dam	Year commissioned	Storage capacity (10^6 m^3)
Komati	South Africa	Nooitgedacht	1962	81
Komati	South Africa	Vygeboom	1971	84
Komati	Swaziland	Maguga	2002	332
Komati	Swaziland	Sand river	1966	49
Lomati	South Africa	Driekoppies	1998	251
Crocodile	South Africa	Kwena	1984	155
Crocodile	South Africa	Witklip	1979	12
Crocodile	South Africa	Klipkopje	1979	12
Sabie	South Africa	Da Gama	1979	14
Sabie	South Africa	Injaka	2001	120
Sabie	Mozambique	Corumana	1988	879
Total				1989

Table 2. Land use and water use change from 1950's to 2004 in Komati, Crocodile and Sabie sub-catchments. Source: adapted from TPTC (2011).

		1950's	1970's	1996	2004
Komati	Irrigation area (km^2)	17.6	144.1	385.1	512.4
	Afforested area (km^2)	247	377	661	801
	Domestic water use ($10^6\,m^3\,a^{-1}$)	0.5	7.7	15.5	19.7
	Industrial and mining water use ($10^6\,m^3\,a^{-1}$)	0	0	0.5	0.5
	Water Transfers out ($10^6\,m^3\,a^{-1}$):				
	To Power stations in South Africa	3.4	103	98.1	104.7
	To irrigation in Swaziland	0	111.8	122.2	121.8
Crocodile	Irrigation area (km^2)	92.8	365.8	427	510.7
	Afforested area (km^2)	375	1550	1811	1941
	Domestic water use ($10^6\,m^3\,a^{-1}$)	3	12.2	33.6	52.4
	Industrial and mining water use ($10^6\,m^3\,a^{-1}$)	0.1	7.5	19.8	22.3
Sabie	Irrigation area (km^2)	27.7	68.4	113.4	127.6
	Afforested area (km^2)	428	729	708	853
	Domestic water use ($10^6\,m^3\,a^{-1}$)	2.4	5.3	13	26.7
	Industrial and mining water use ($10^6\,m^3\,a^{-1}$)	0	0	0	0

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Table 3. Hydrometric stations analyzed, location, catchment area, data length and missing data.

	Station	Latitude	Longitude	River and location	Catchment Area (km^2)	Data Available	Period analysed for trends	Missing Data
Komati	X1H001	−26.04	31.00	Komati River @ Hooggenoeg	5499	1909 – 2012	1970–2011 (42 years)	8.0 %
	X1H003	−25.68	31.78	Komati River @ Tonga	8614	1939 – 2012	1970–2011 (42 years)	6.8 %
	X1H014	−25.67	31.58	Mlumati River @ Lomati	1119	1968 – 2012	1978–2011 (34 years)	0.5 %
	X1H016	−25.95	30.57	Buffelspruit @ Doornpoort	581	1970 – 2012	1970–2011 (42 years)	3.4 %
	X1H021	−26.01	31.08	Mtsoli River @ Diepgezet	295	1975 – 2012	1976–2011 (36 years)	2.7 %
Crocodile	X2H005	−25.43	30.97	Nels River @ Boschrand	642	1929 – 2012	1970–2011 (42 years)	0.8 %
	X2H006	−25.47	31.09	Krokodil River @ Karino	5097	1929 – 2012	1970–2011 (42 years)	0.1 %
	X2H008	−25.79	30.92	Queens River @ Sassenheim	180	1948 – 2012	1970–2011 (42 years)	0.5 %
	X2H010	−25.61	30.87	Noordkaap River @ Bellevue	126	1948 – 2012	1970–2011 (42 years)	5.7 %
	X2H011	−25.65	30.28	Elands River @ Geluk	402	1956 – 1999	1957–1999 (43 years)	0.9 %
	X2H012	−25.66	30.26	Dawsons Spruit @ Geluk	91	1956 – 2012	1970–2011 (42 years)	0.3 %
	X2H013	−25.45	30.71	Krokodil River @ Montrose	1518	1959 – 2012	1970–2011 (42 years)	1.6 %
	X2H014	−25.38	30.70	Houtbosloop @ Sudwalaskraal	250	1958 – 2012	1970–2011 (42 years)	5.1 %
	X2H015	−25.49	30.70	Elands River @ Lindenau	1554	1959 – 2012	1970–2011 (42 years)	3.1 %
	X2H016	−25.36	31.96	Krokodil River @ Tenbosch	10365	1960 – 2012	1970–2011 (42 years)	5.6 %
	X2H022	−25.54	31.32	Kaap River @ Dolton	1639	1960 – 2012	1970–2011 (42 years)	5.7 %
	X2H024	−25.71	30.84	Suidkaap River @ Glenthorpe	80	1964 – 2012	1970–2011 (42 years)	1.7 %
	X2H031	−25.73	30.98	Suidkaap River @ Bornmans Drift	262	1966 – 2012	1966–2011 (46 years)	5.0 %
	X2H032	−25.51	31.22	Krokodil River @ Weltevrede	5397	1968 – 2012	1970–2011 (42 years)	2.4 %
	X2H036	−25.44	31.98	Komati River @ Komatipoort	21 481	1982 – 2012	1983–2011 (28 years)	4.1 %
	X2H046	−25.40	31.61	Krokodil River @ Riverside	8473	1985 – 2012	1986–2011 (26 years)	2.0 %
	X2H047	−25.61	30.40	Swartkoppiesspruit @ Kindergoed	110	1985 – 2012	1986–2011 (26 years)	2.2 %
Sabie	X3H001	−25.09	30.78	Sabie River @ Sabie	174	1948 – 2012	1970–2011 (42 years)	0.8 %
	X3H002	−25.09	30.78	Klein Sabie River @ Sabie	55	1963 – 2012	1970–2011 (42 years)	0.4 %
	X3H003	−24.99	30.81	Mac-Mac River @ Geelhoutboom	52	1948 – 2012	1970–2011 (42 years)	0.5 %
	X3H004	−25.08	31.13	Noordsand River @ De Rust	200	1948 – 2012	1970–2011 (42 years)	3.9 %
	X3H006	−25.03	31.13	Sabie River @ Perry's Farm	766	1958 – 2000	1970–1999 (30 years)	2.6 %
	X3H008	−24.77	31.39	Sand River @ Exeter	1064	1967 – 2011	1968–2011 (43 years)	15.5 %
	X3H011	−24.89	31.09	Marite River @ Injaka	212	1978 – 2012	1979–2011 (32 years)	7.6 %
	X3H015	−25.15	31.94	Sabie River @ Lower Sabie Rest Camp	5714	1986 – 2012	1988–2011 (24 years)	8.2 %
	X3H021	−24.97	31.52	Sabie River @ Kruger Gate	2407	1990 – 2012	1991–2011 (21 years)	10.8 %
Lower Incomati	E23	−25.44	31.99	Incomati River @ Ressano Garcia	21 200	1948 – 2011	1970–2011 (42 years)	9.0 %
	E43	−25.03	32.65	Incomati River @ Magude	37 500	1952 – 2011	1970–2011 (42 years)	3.5 %

Table 4. Hydrologic parameters used in Range of Variability Approach (Richter et al., 1996).

Indicators of Hydrologic Alteration Group	Regime Characteristics	Hydrological parameters
Group 1: Magnitude of monthly water conditions	Magnitude timing	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude duration	Annual minima and maxima based on one, three, seven, thirty and ninety day(s) mean
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1 day maximum and minimum
Group 4: Frequency and duration of high/low pulses	Frequency and duration	No. of high and low pulses each year
		Mean duration of high and low pulses within each year (days)
Group 5: Rate/Frequency of water condition changes	Rates of change of frequency	Means of all positive and negative differences between consecutive daily values
		No. of rises and falls

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Table 5. Description of rainfall stations analyzed for trends, also the long term Mean Annual Precipitation (MAP) in mm a^{-1}, the standard variation, and detection of trend (confidence level of 95 % using Spearman Test) and occurrence change point (using Pettitt Test followed by T test of stability of mean and F test of stability of variance).

Name	Station ID	Latitude	Longitude	Altitude [m a.s.l.]	MAP [mm]	P Reliable [%]	Analysis for the period 1950 to 2011 Mean [mm a^{-1}]	St.Dev. [mm a^{-1}]	Trend Spearman	Pettitt
Machadodorp	0517430 W	−25.67	30.25	1563	781	79.6	773	134		
Badplaas (Pol)	0518088 W	−25.97	30.57	1165	829	90.6	817	153		
Kaapsehoop	0518455 W	−25.58	30.77	1564	1443	78.5	1461	286		Decr (1975)
Mac Mac (Bos)	0594539 W	−24.98	30.82	1295	1463	75.1	1501	287		
Spitskop (Bos)	0555579 W	−25.15	30.83	1395	1161	68.5	1197	266	Decr	Decr (1978)[a]
Alkmaar	0555567 W	−25.45	30.83	715	830	95.2	874	172		
Oorschot	0518859 W	−25.80	30.95	796	787	92.2	775	185		
Bosbokrand (Pol)	0595110 W	−24.83	31.07	778	982	82.4	919	297		Decr (1978)[a]
Pretoriuskop	0556460 W	−25.17	31.18	625	707	60.0	734	188		
Riverbank	0519310 W	−25.67	31.23	583	683	70.5	782	163	Incr	Incr (1977)[b]
Piggs Pig	0519448 A	−25.97	31.25	1029	1024	40.1	1075	315	Decr	Decr (1978)[a]
Skukuza	0596179 W	−25.00	31.58	300	560	63.1	566	140		
Riverside	0557115 W	−25.42	31.60	315	547	66.5	520	187		
Satara	0639504 W	−24.40	31.78	257	568	42.1	602	151	Incr	Incr (1971)
Fig Tree	0520589 W	−25.82	31.83	256	591	63.4	594	145	Decr	Decr (1978)[a]
Tsokwane	0596647 W	−24.78	31.87	262	540	66.1	544	134		Incr (1971)[a]
Krokodilbrug	0557712 W	−25.37	31.90	192	584	62.9	590	147		
Moamba	P821 M	−25.60	32.23	108	632	63.9	633	185		
Xinavane	P10 M	−25.07	32.87	18	853	76.2	773	241		
Manhica	P63 M	−25.40	32.80	33	883	86.2	903	275		Incr (1970)[b]

[a] Significant change with 2.5 % significance level with T test of stability of mean.
[b] Significant change with 2.5 % significance level with T test of stability of mean and F test of stability of variance.
Explanatory Note: MAP is the Mean Annual Precipitation, and P reliable is the percentage of reliable data for the rainfall station, as assessed by Lynch (2003) for the period 1905 to 1999. The mean refers to the average of total annual precipitation for the period of 1950 to 2011. On the column trend Spearman only stations that had trend significant at 95 % confidence level are indicated with Decr or Incr, corresponding to decreasing or increasing trend, respectively. On the column Pettitt, the direction of change and year are indicated, as well as the significance of the change point.

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Table 6. Hydrological indicators of main sub-catchments.

STREAMFLOW INDICATORS Period of Analysis:	UNITS	KOMATI X1H003 – TONGA 1970–2011 (42 years)		CROCODILE X2H016 – TENBOSH 1970–2011 (42 years)		INCOMATI X2H036 – KOMATIPOORT 1983–2011 (28 years)		SABIE X3H015 – LOWER SABIE 1988–2011 (24 years)		INCOMATI E43 – MAGUDE 1970–2011 (42 years)	
Drainage area	km^2	8614		10 365		21 481		5714		37 500	
		Median	CD	Median	CD	Median	CD	Median	CD	Median	CD
Annual*	$m^3 s^{-1}$	16.94	*2.14*	21.35	*1.97*	34.28	*2.11*	17.35	*2.31*	47.44	*2.01*
Oct	$m^3 s^{-1}$	3.95	*1.47*	2.54	*1.88*	2.24	*1.87*	3.08	*0.92*	8.72	*1.21*
Nov	$m^3 s^{-1}$	5.72	*1.94*	5.75	*2.35*	7.09	*3.88*	4.81	*1.09*	16.14	*1.49*
Dec	$m^3 s^{-1}$	11.46	*2.09*	15.07	*1.48*	18.79	*2.63*	10.83	*1.49*	22.91	*2.90*
Jan	$m^3 s^{-1}$	17.26	*1.82*	20.68	*1.47*	34.47	*1.52*	18.52	*1.35*	37.96	*1.35*
Feb	$m^3 s^{-1}$	25.09	*1.95*	31.37	*2.01*	29.77	*2.80*	16.33	*1.84*	45.09	*3.21*
Mar	$m^3 s^{-1}$	18.33	*1.74*	27.15	*1.63*	42.15	*1.90*	19.51	*2.30*	51.75	*2.32*
Apr	$m^3 s^{-1}$	11.64	*1.74*	19.82	*1.37*	24.10	*2.13*	13.69	*1.13*	34.90	*2.03*
May	$m^3 s^{-1}$	8.03	*1.41*	9.11	*1.68*	9.98	*2.16*	7.04	*1.64*	17.85	*1.86*
Jun	$m^3 s^{-1}$	4.96	*1.90*	5.66	*1.62*	7.10	*2.45*	5.64	*1.25*	14.04	*1.44*
Jul	$m^3 s^{-1}$	3.77	*1.98*	4.56	*1.48*	4.72	*2.28*	3.79	*1.18*	10.41	*1.47*
Aug	$m^3 s^{-1}$	2.67	*1.63*	2.63	*1.71*	2.51	*1.35*	3.40	*1.08*	8.46	*1.41*
Sep	$m^3 s^{-1}$	2.43	*1.47*	2.08	*1.81*	2.24	*1.51*	2.69	*1.15*	7.06	*1.11*
1 day minimum	$m^3 s^{-1}$	0.31	*4.04*	0.24	*2.64*	0.14	*5.29*	1.45	*1.13*	2.49	*1.48*
3 day minimum	$m^3 s^{-1}$	0.38	*3.38*	0.32	*2.16*	0.25	*3.76*	1.53	*1.08*	2.71	*1.76*
7 day minimum	$m^3 s^{-1}$	0.59	*2.55*	0.40	*2.88*	0.33	*4.35*	1.60	*1.16*	3.01	*1.61*
30 day minimum	$m^3 s^{-1}$	1.46	*2.13*	1.52	*1.79*	1.29	*2.08*	2.01	*1.12*	4.84	*1.37*
90 day minimum	$m^3 s^{-1}$	3.69	*1.47*	3.45	*1.34*	3.17	*2.09*	3.02	*1.23*	8.14	*1.38*
1 day maximum	$m^3 s^{-1}$	134.4	*1.26*	142.2	*1.38*	274.3	*1.00*	113	*2.51*	381.5	*1.80*
3 day maximum	$m^3 s^{-1}$	102.9	*1.50*	126.9	*1.33*	232.9	*1.15*	87.62	*2.60*	344.1	*1.74*
7 day maximum	$m^3 s^{-1}$	81.79	*1.59*	107.4	*1.20*	201.4	*1.13*	62.55	*2.27*	273.7	*1.56*
30 day maximum	$m^3 s^{-1}$	54.39	*1.45*	76.98	*1.28*	109.6	*1.33*	37.66	*1.93*	156.7	*1.45*
90 day maximum	$m^3 s^{-1}$	39.19	*1.33*	45.08	*1.16*	68.69	*1.71*	28.06	*1.47*	102	*1.32*
Date of minimum	Julian Date	275	*0.10*	274	*0.12*	281.5	*0.15*	278.5	*0.06*	290.5	*0.21*
Date of maximum	Julian Date	38.5	*0.16*	33	*0.11*	35.5	*0.19*	20.5	*0.17*	39.5	*0.14*
Low pulse count	No	6	*1.63*	4	*1.63*	5	*1.55*	4	*1.00*	3	*1.33*
Low pulse duration	Days	5.5	*1.41*	5	*1.60*	3.5	*0.71*	6.5	*1.69*	6.75	*2.09*
High pulse count	No	6	*0.75*	4	*1.25*	5	*0.95*	4	*0.69*	4	*0.75*
High pulse duration	Days	4	*1.31*	4	*2.13*	4.5	*1.28*	5	*2.10*	8.5	*1.03*
Rise rate	$m^3 s^{-1}$	0.7095	*1.39*	0.64	*0.98*	1.161	*1.38*	0.404	*1.12*	1.058	*1.43*
Fall rate	$m^3 s^{-1}$	−0.7295	*−0.98*	−0.61	*−0.78*	−1.38	*−1.28*	−0.2398	*−1.10*	−0.6278	*−2.31*
Number of reversals	No	111.5	*0.26*	113	*0.42*	121	*0.18*	95	*0.29*	86	*0.49*

[*] On the annual statistics mean and coefficient of variation were used.

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Table 7. Trends of the hydrological indicators for the period 1970–2011. In bold are significant trends at 95 % confidence level.

STREAMFLOW INDICATORS Period of Analysis:	KOMATI X1H003 – TONGA 1970–2011 (42 years)		CROCODILE X2H016 – TENBOSH 1970–2011 (42 years)		SABIE X3H015 – LOWER SABIE 1988–2011 (24 years)		INCOMATI X2H036 – KOMATIPOORT 1983–2011 (28 years)		INCOMATI E43 – MAGUDE 1970–2011 (42 years)	
Drainage area [km^2]	8614		10 365		5714		21 481		37 500	
	Slope	*P* value	Slope	*P* value	Slope	*P* value	Slope	*P* value	Slope	*P* value
Oct	**−0.285**	***0.05***	−0.052	*0.5*	0.017	*0.5*	−0.017	*0.5*	−0.313	*0.25*
Nov	−0.254	*0.1*	−0.006	*0.5*	0.263	*0.5*	0.020	*0.5*	−0.165	*0.5*
Dec	−0.194	*0.5*	−0.090	*0.5*	0.199	*0.5*	0.783	*0.5*	−0.087	*0.5*
Jan	−0.437	*0.5*	−0.023	*0.5*	1.493	*0.25*	1.979	*0.25*	−0.960	*0.5*
Feb	−1.027	*0.1*	−0.927	*0.25*	0.544	*0.5*	−0.486	*0.5*	**−2.847**	***0.05***
Mar	−0.360	*0.5*	−0.397	*0.5*	0.390	*0.5*	−0.112	*0.5*	−1.346	*0.5*
Apr	−0.082	*0.5*	−0.007	*0.5*	0.899	*0.25*	1.532	*0.25*	−0.195	*0.5*
May	−0.225	*0.1*	−0.045	*0.5*	0.416	*0.5*	0.788	*0.5*	−0.365	*0.5*
Jun	**−0.215**	***0.025***	0.059	*0.5*	0.270	*0.5*	0.470	*0.5*	−0.045	*0.5*
Jul	**−0.179**	***0.005***	0.060	*0.5*	0.219	*0.5*	0.171	*0.5*	−0.039	*0.5*
Aug	−0.074	*0.1*	0.105	*0.5*	0.134	*0.25*	0.312	*0.5*	0.090	*0.5*
Sep	−0.029	*0.5*	0.134	*0.5*	0.081	*0.5*	0.218	*0.5*	0.166	*0.25*
1 day minimum	**−0.027**	***0.025***	−0.015	*0.25*	0.061	*0.1*	0.003	*0.5*	**0.139**	***0.001***
3 day minimum	**−0.029**	***0.025***	−0.015	*0.25*	0.061	*0.1*	0.004	*0.5*	**0.127**	***0.005***
7 day minimum	**−0.038**	***0.05***	−0.015	*0.5*	0.064	*0.1*	0.004	*0.5*	0.094	***0.05***
30 day minimum	**−0.069**	***0.025***	−0.025	*0.25*	0.058	*0.25*	0.033	*0.5*	0.054	*0.5*
90 day minimum	**−0.115**	***0.01***	−0.059	*0.25*	0.131	*0.1*	0.038	*0.5*	−0.054	*0.5*
1 day maximum	−5.143	*0.25*	−5.425	*0.25*	−2.743	*0.5*	−12.070	*0.25*	**−10.580**	***0.025***
3 day maximum	−3.749	*0.25*	−3.670	*0.25*	−1.379	*0.5*	−8.171	*0.5*	**−9.254**	***0.025***
7 day maximum	−2.361	*0.25*	−2.427	*0.25*	0.014	*0.5*	−3.742	*0.5*	**−6.722**	***0.05***
30 day maximum	−1.022	*0.25*	−1.023	*0.25*	0.662	*0.5*	0.092	*0.5*	−3.400	*0.1*
90 day maximum	−0.671	*0.25*	−0.576	*0.5*	0.789	*0.5*	0.934	*0.5*	−2.147	*0.25*
Number of zero days	0.690	*0.25*	−0.005	*0.5*	0	*0.5*	0.032	*0.5*	−0.080	*0.5*
Base flow index	−0.001	*0.25*	0.000	*0.5*	0.004	*0.5*	0.001	*0.25*	**0.007**	***0.001***
Date of minimum	−0.686	*0.5*	0.354	*0.5*	0.548	*0.5*	−0.420	*0.5*	1.374	*0.5*
Date of maximum	0.817	*0.5*	0.347	*0.5*	−3.222	*0.5*	0.288	*0.5*	0.617	*0.5*
Low pulse count	0.132	*0.1*	**0.238**	***0.001***	−0.045	*0.5*	0.185	*0.5*	0.043	*0.25*
Low pulse duration	0.068	*0.5*	−0.140	*0.5*	−0.669	*0.1*	−0.297	*0.25*	−0.602	*0.5*
High pulse count	**−0.127**	***0.005***	0.007	*0.5*	−0.023	*0.5*	−0.096	*0.25*	−0.068	***0.05***
High pulse duration	0.029	*0.5*	**−1.263**	***0.01***	1.081	*0.25*	0.144	*0.5*	−0.103	*0.5*
Rise rate	−0.007	*0.5*	−0.008	*0.5*	0.005	*0.5*	0.017	*0.5*	**−0.034**	***0.05***
Fall rate	0.003	*0.5*	**−0.013**	***0.05***	−0.007	*0.5*	−0.012	*0.5*	−0.007	*0.5*
Number of reversals	0.574	*0.1*	**1.083**	***0.01***	0.723	*0.5*	0.560	*0.5*	**0.764**	***0.005***

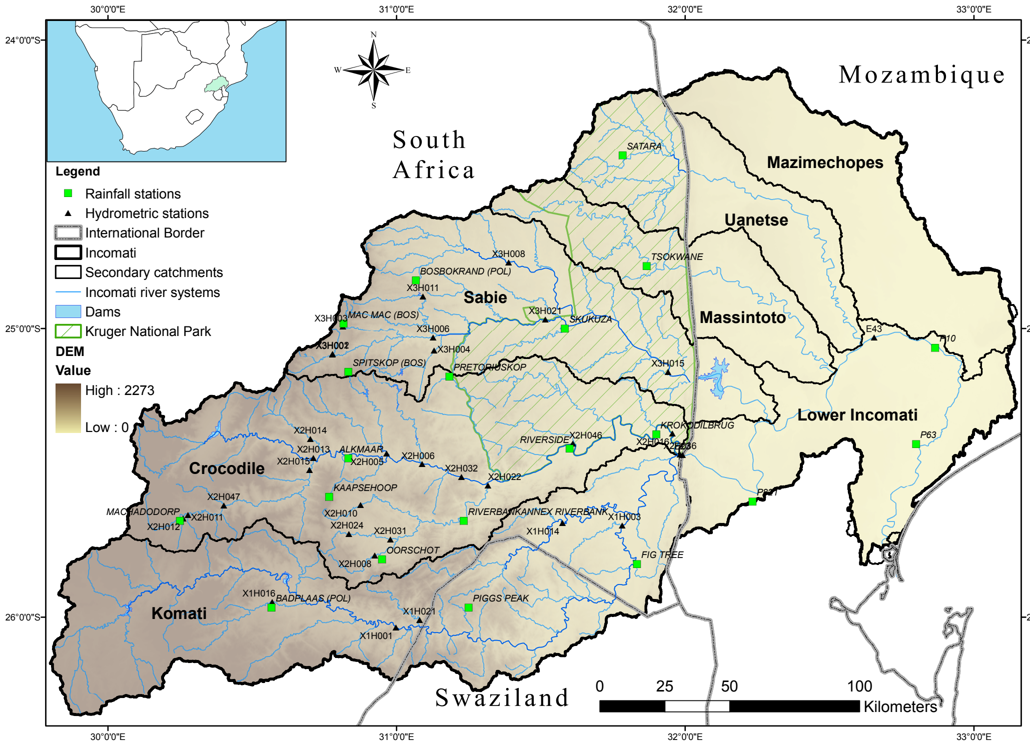

Figure 1. Map of location of the study area, illustrating the main sub-catchments, the hydrometric and rainfall stations analyzed, and the basin topography and dams.

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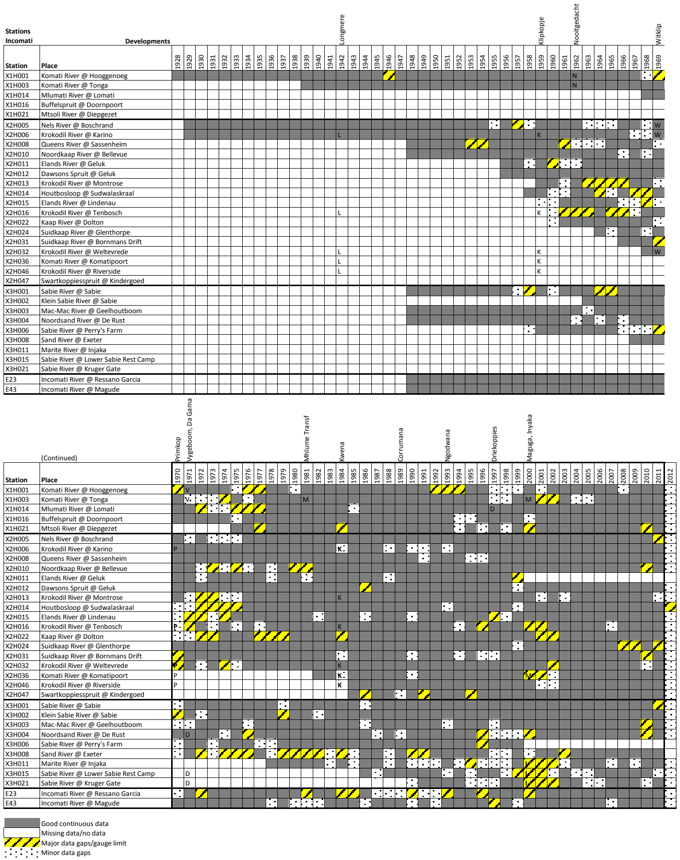

Figure 2. Streamflow data used on this study, with indication of time series length, data quality, missing data. Major developments in the basin, such as dams, are on the top horizontal line on the year they were commissioned; indication is made of the gauges affected by the developments by the initial letter of the dam.

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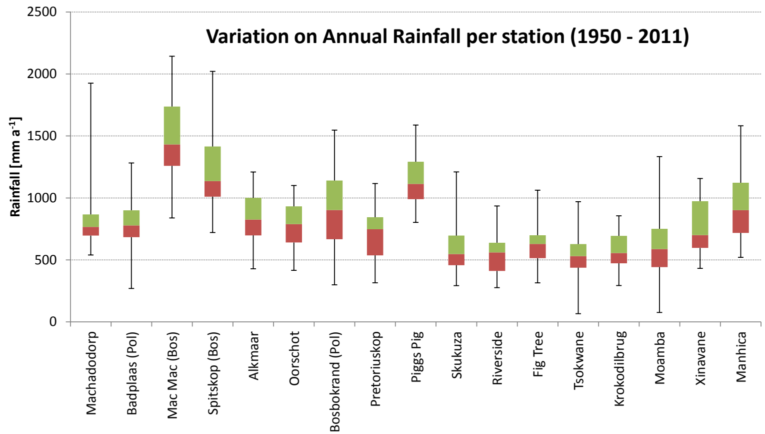

Figure 3. Box plot illustrating the spatial variation of annual rainfall across the Incomati Basin (median, 25 %, 75 % are shown by the green and red boxes; the lines illustrate the range). The stations are presented from west to east, along the basin profile.

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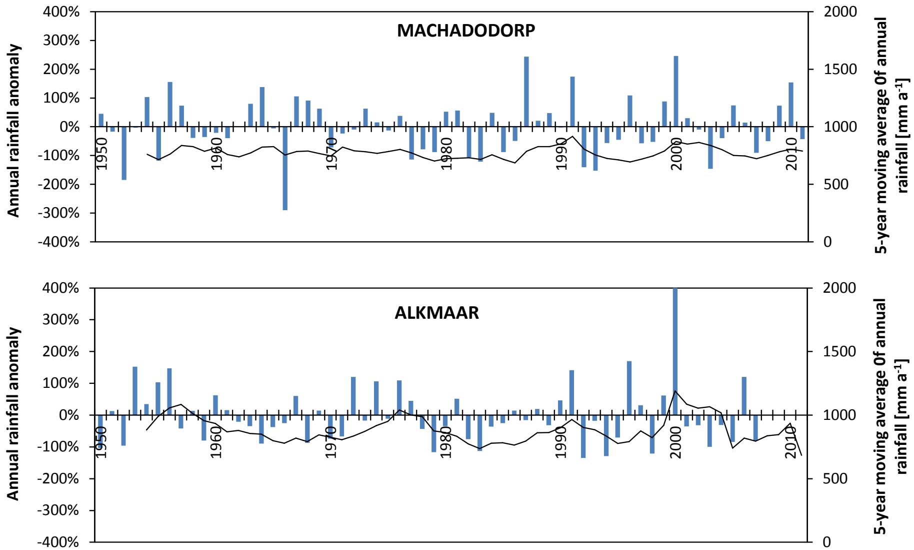

Figure 4. Annual rainfall anomalies (blue bars), computed as the deviation from the long-term average 1950–2010 and the 5 year moving average of annual rainfall (black line, legend on the right).

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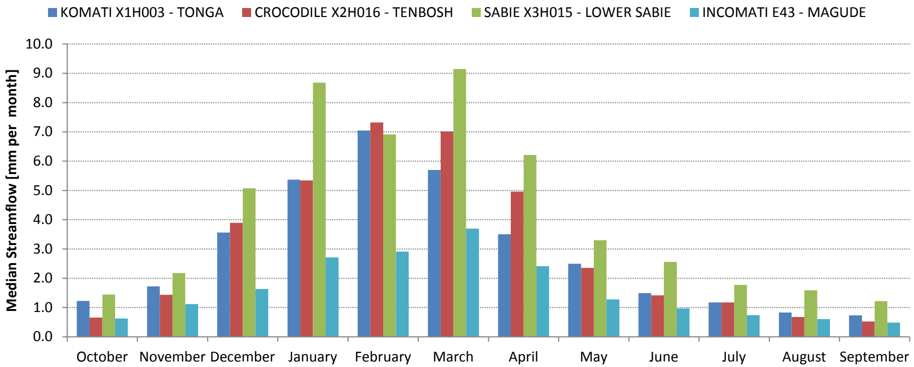

Figure 5. Median of observed daily streamflow for the gauges located at the outlet of major sub-catchments Komati, Crocodile, Lower Sabie and Incomati (based on daily time series from 1970 to 2011).

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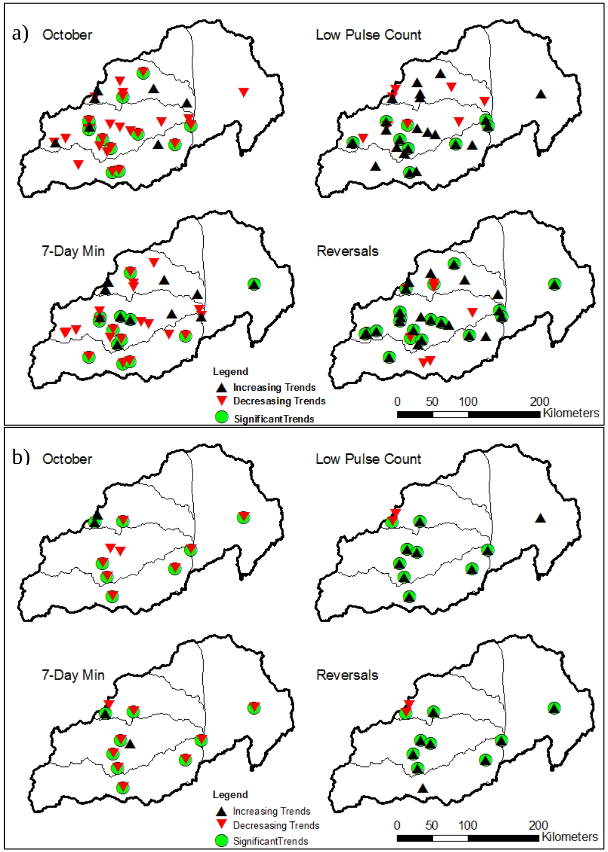

Figure 6. Trends of different indicators of streamflow: **(a)** for period 1970–2011; **(b)** for period 1950–2011.

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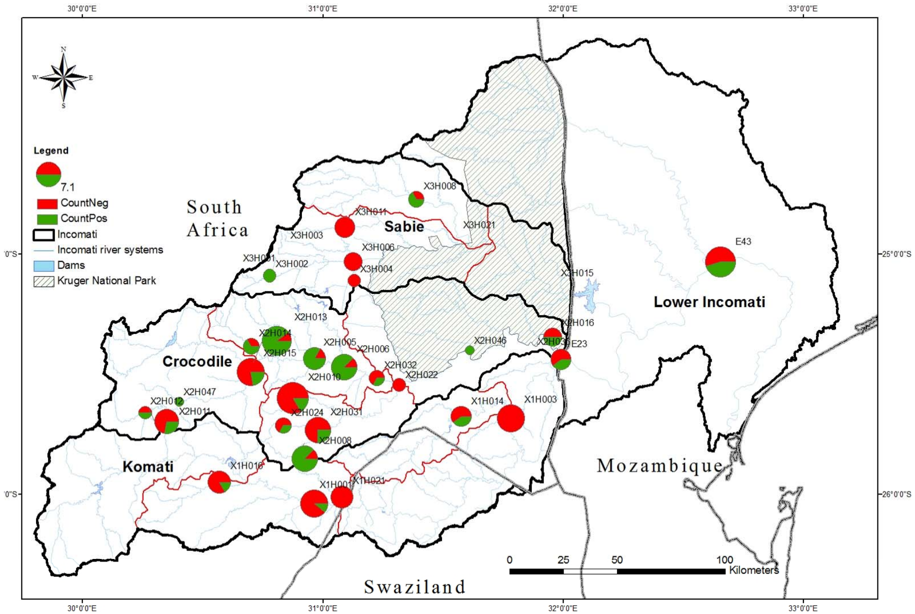

Figure 7. Count of significant trends. Declining trends are in red and increasing trends in green. The size of the pie is proportional to the total number of significant trends.

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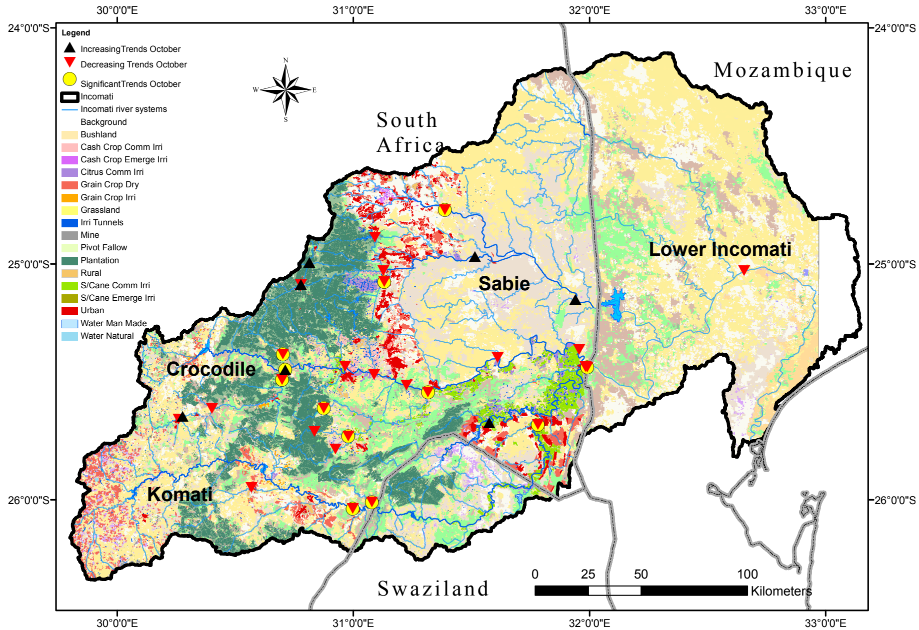

Figure 8. Land use land cover map of Incomati (ICMA, 2010; TPTC, 2011) and streamflow trends in the month of October.

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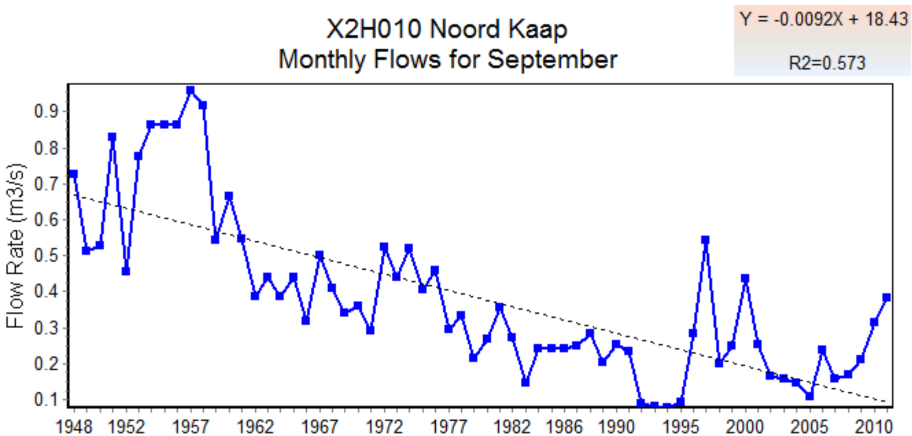

Figure 9. Plot of median monthly flows for September for the entire time series (1949–2011) on the Noord Kaap Gauge, located on the Crocodile sub-catchment.

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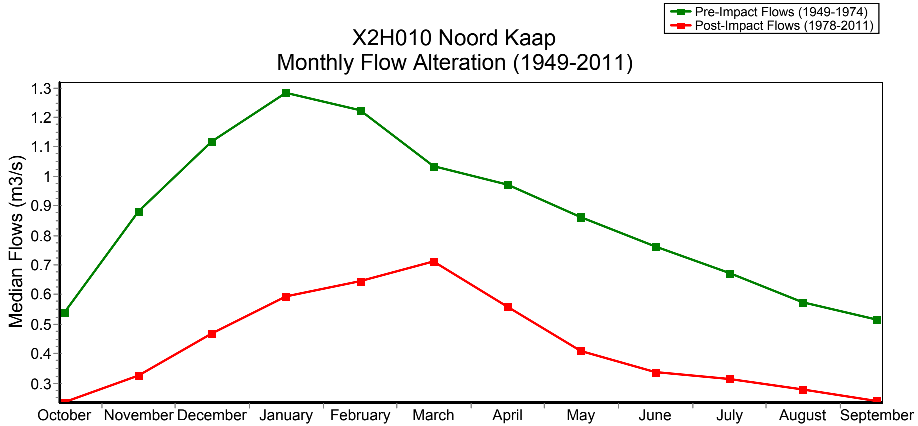

Figure 10. Plot of median monthly flows for 2 periods (1949–1974 and 1978–2011) on the Noord Kaap Gauge, located on the Crocodile sub-catchment.

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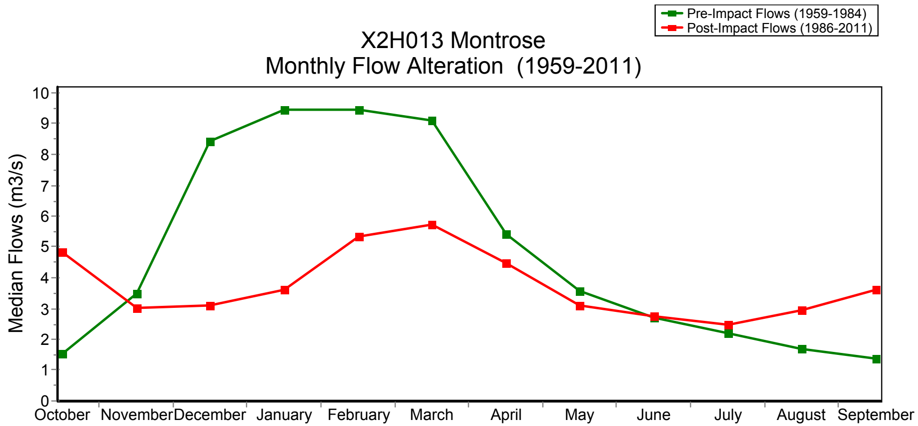

Figure 11. Impact of Kwena Dam (commissioned in 1984) on streamflows of the Crocodile River, Montrose Gauge X2H013.

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