Groundwater as an emergency source for drought mitigation in the Crocodile River catchment, South Africa

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Abstract

Global climate change has received much attention worldwide in the scientific as well as in the political community, inter alia, indicating that changes in precipitation, extreme droughts and floods may threaten increasingly many regions. Drought is a natural phenomenon that may cause social, economical and environmental damages to the society. In this study, we assess the drought intensity and severity and the groundwater potential to be used as a supplementary source of water to mitigate drought impacts in the Crocodile River catchment, a water-stressed sub-catchment of the Incomati River catchment in South Africa. The research methodology consists mainly of three parts. First, the spatial and temporal variation of the meteorological and hydrological drought severity and intensity over the catchment were evaluated. The Standardized Precipitation Index (SPI) was used to analyse the meteorological drought and the Standardized Runoff Index (SRI) was used for the hydrological drought. Second, the water deficit in the catchment during the drought period was computed using a simple water balance method. Finally, a groundwater model was constructed in order to assess the feasibility of using groundwater as an emergency source for drought impact mitigation. Results show that the low rainfall areas are more vulnerable to severe meteorological droughts (lower and upper crocodile). Moreover, the most water stressed sub-catchments with high level of water uses but limited storage, such as the Kaap located in the middle catchment and the Lower Crocodile sub-catchments, are more vulnerable to severe hydrological droughts. The analysis of the potential groundwater use during droughts showed that a deficit of 97 Mm$^3$/yr could be supplied from groundwater without considerable adverse impacts on the river base flow and groundwater storage. Abstraction simulations for different scenarios of extremely severe droughts reveal that it is possible to use groundwater to cope with the droughts in the catchment. However, local groundwater exploitation in Nelspruit and White River sub-catchment will cause large drawdowns (>10 m) and high base flow reduction (>20%). This case study shows that conjunctive water management of groundwater and surface water resources is the necessary to mitigate the impacts of droughts.
1. Introduction

Global climate change is one of the serious environmental challenges which the world is facing this century (IPCC 2013). It is related to systematic changes of the entire world’s weather and climate patterns beyond the natural variability limits, and increased droughts are among the consequences. Drought is a natural phenomenon that may cause serious social, economical and environmental damages, in particular in areas where the water resources are already highly utilised. A number of different reactive and proactive measures on regional or national scale can be used to reduce its impacts. These measures include: the use of resilience buildings of rain fed farming system for water harvesting for supplemental irrigation in semi-arid regions (Rockström, 2003); the use of groundwater, use of storages in mountain rivers where precipitation is higher, and the construction of water distribution and water storage systems (MacDonald, 2007); and the artificial groundwater recharge with excess water form wet periods and reuse of treated wastewater (Zhou et al., 2011). Along the same lines, Pavelic et al. (2012) proposes to capture the peak flow (surplus of water) during the wet season and recharge shallow alluvial aquifers in a distributed manner upstream of the flood prone areas. Two large regional projects have been conducted in Africa to investigate groundwater potential for water supply during the drought. Groundwater and Drought Management Project (SADC, 2014) has developed strategic regional approach to support and enhance the capacity of Southern African Development Community in the definition of drought management policies, specifically in relation to the role, availability, and supply potential of groundwater resources. Groundwater Resources Investigation for Drought Mitigation in Africa Programme (GRIDMAP, 2014) aimed at assessing the availability of groundwater resources in the Horn of Africa and determining how much groundwater resources can be utilized safely for emergency and long-term development demands.

The Incomati river catchment is a transboundary river catchment located in the south-eastern part of Africa which flows through South Africa, Swaziland and Mozambique and discharges into the Indian Ocean. The river catchment is characterised as a semi-arid climate subject to hydrological extremes: severe droughts and floods. The Crocodile River is one of the most important tributaries of Incomati. In the Crocodile catchment, data and knowledge are limited regarding the groundwater resources and its potential for use during the drought period. One of the first attempts to provide maps of sustainable groundwater harvest potential (GHP) was by Baron et al. (1998), which was based on hydrogeological maps developed by Vegter (1995). The GHP maps cover the whole South Africa and provide a first estimate of the maximum mean annual amount of water that can be abstracted from groundwater without depleting the aquifers. However, the use of these maps for local groundwater management planning is limited due to high uncertainty. The GHP maps were updated by Water Systems Management (2001) and
DWAF (2006). However, the update in the part of the Incomati catchment is largely based on interpolation from some experimental data from the surrounding catchments, thus associated with high uncertainty.

Some groundwater studies have been carried out recently in the Incomati catchment. Consultec and BKS (2001) quantified groundwater availability in the Incomati catchment aiming to assess its potential contribution to the total water resources of the catchment. Mauritius et al. (2010) made a groundwater potential assessment study for the whole Incomati catchment based on the aquifer classifications suggested by (DWAF, 2006). Their study produced maps of the Incomati groundwater availability (in terms of low, medium or high water availability) and the average well yield of Incomati, without distinction between wet and dry periods. Some groundwater studies have been done in the Kruger National Park, a conservation area partly located in the Lower Crocodile (Fundisi et al., 2012; Niekerk et al., 2012; Fischer et al., 2010; Fischer et al., 2009; Leyland et al., 2008). So far, many of the groundwater potential assessment studies were performed at large scale, but no groundwater potential assessment study has been carried out in the Crocodile River catchment.

Due to the intense agricultural activity, the Crocodile River catchment is highly water stressed. The surface water is insufficient to meet the demands especially during drought periods. Small scale farmers are the most vulnerable and affected by drought hazards. The downstream country Mozambique is also highly affected when droughts occur in this catchment because of reduced transboundary flows (Zaag and Vaz, 2003). In order to mitigate and manage water shortage during droughts, measures are being taken on the catchment scale. These measures include water transfer from adjacent catchments (Sabile and Komati) into the Crocodile river catchment, storage in reservoirs, water restrictions to avoid system failure and simple management models are being setup to quantify the risks (Mauritius et al., 2010). Although groundwater is used locally, it is not a main component of the actual drought mitigation and management plan. However, groundwater has been considered as a potential source to mitigate the impact of droughts and help to meet future increased water demand in the region (DWA, 2013).

Given the vulnerability of the Crocodile catchment to climate change, the necessity in further expanding agricultural activities and lack of knowledge on groundwater availability in drought periods, research on drought and the feasibility of using groundwater as an emergency source to mitigate its impacts is of great importance. The specific objectives of this study are: i) classifying spatially the meteorological and hydrological droughts in terms of intensity and severity, ii) assessing the water availability versus demand
in the catchment during the drought periods, and iii) formulating drought mitigation strategies by
assessing the groundwater availability during drought periods.

2. Material and methods

2.1. Study area

The Crocodile River catchment has an area of around 10,446 km$^2$ and presents a wide range of elevation
varying from around 2,030m in the most upstream part and gradually decreasing to 140 m at the outlet
(Figure 1). The main economic activities in the catchment are agriculture and forestry, with urban
development and mining activities occupying a secondary role. According to the Incomati Water
Availability Assessment Study (DWAF, 2009) the total area of irrigated agriculture and commercial
forestry in the Crocodile catchment was 2,452 km$^2$ in 2004 which corresponds to around 61% of the total
irrigated area in the whole Incomati catchment.

The catchment is characterised by semi-arid climate with an annual rainfall and potential evaporation of
850mm/yr and 1,380mm/yr, respectively. The precipitation is highly seasonal; more than 80% of the
annual rainfall falls during the summer half-year October-March. The precipitation also varies over the
catchment, is higher in the middle part of the catchment where there are mountains and lower in the
upstream and downstream regions. Potential evaporation decreases from downstream (low altitudes) to
upstream (high altitudes).

The geology of the Crocodile catchment is complex. Around 60% of the total area (in the middle and
lower regions) consists mainly of granite and gneiss. It is characterized in the south by sedimentary rocks
(such as arenite) and volcanic rocks (mainly lavas) of the Barberton sequence. In the west it is composed
of a complex mixture of sedimentary rocks (such as arenite and shale), volcanic (mainly andesite) and
dolomitic rocks of the Transvaal sequence. In the east it contains a very small area of sedimentary rocks
(such as shale) and volcanic rocks (mainly basalt and rhyolite) of the Karoo sequence. The aquifers of the
Crocodile catchment are mostly consisted of regolith materials.

2.2. Data sets

Lynch (2003) developed a rainfall database of the South African region with data starting from around
1900 and ending in 2001. The database consists of daily precipitation records and data quality control
gathered from the three main custodians of rainfall data in South Africa which include: SAWS (South
Africa Weather Service), SASRI (South Africa Sugarcane Research Institution) and ARC (Agricultural
Research Council). Additionally, a large number of municipalities, private companies and individuals in
South Africa also contributed with rainfall data to the database. Lynch (2003) computed the percentage of non-missing data of the time series for each station.

Data from this database was used and from 2001 onwards, data provided only by SAWS was used. 17 precipitation stations with low percentage of missing data (Table 1) and a good spatial variability (Figure 1) were selected. The time period for less missing data corresponds to the period of 1940 to 2011. Similarly, 11 gauging stations of river discharges were selected based on the length of the time series (at least 30 years of data), missing data in the time series (Table 1) and spatial variability of the stations (Figure 1).

The Crocodile catchment has around 320 groundwater wells operated by DWA. Around 25% of the wells do not have any water level measurement. Furthermore, there is only one water level measurement per year in almost all the wells. Only a few wells have time series of water levels which covers the period from 2000 onwards. Moreover, not many wells have water level measurements in the severe drought periods, especially in the Lower Crocodile. Thus, only 10 wells with water level measurements during drought periods were available for the model calibration (Figure 1).

A land use map was acquired from the Department of Water Affairs (DWA) in South Africa. Reference evapotranspiration data for each sub-catchment was obtained from the DWA study (DWAF, 2009). Topography data consists of 90x90 m² Digital Elevation Model (DEM) of Shuttle Radar Topography Mission (SRTM) from NASA. Hydrogeological characteristics were obtained from a simplified hydrogeological map from the Council of Geosciences of South Africa (see Figure 1). Aquifer parameters such as layers thickness and hydraulic conductivity were provided by the Water Resources of South Africa study (WRC, 2005). Due to the lack of data, the values of specific yield were assigned to the geological formations based on general knowledge available in literature, for instance, Nonner (2010).

2.3. Methods

An overview of the methodology used in this study is presented in Figure 2. The methodology consists of drought classification, water deficit assessment during drought periods, and groundwater modelling for analysing groundwater potential for drought mitigation.

Drought classification

Droughts can be defined as "a decrease of water availability to substantially below the normal condition for a certain place and time" (Loucks and Beek, 2005) and are usually classified as meteorological,
hydrological and agricultural droughts. In this research, we focus on meteorological and hydrological droughts. Several drought indices can be used to identify droughts (Werick et al., 1994; Baykan and Özçelik, 2006; Palmer, 1965, 1968; Willeke, 1994; McKee et al., 1993; Shukla and Wood, 2008). Furthermore, droughts can be classified according to its duration, severity and intensity. Drought duration is the time during which a drought index remains below a certain critical value, whereas drought severity represented as the cumulative of a drought index below a critical value within the drought duration and drought intensity as the average of the drought index over the drought duration (Mishra and Singh, 2010). Comparison of the advantages, disadvantages and applicability of the various drought indices has been reported in the literature (Loucks and Beek, 2005; Zargar et al., 2011; Mishra and Singh, 2010; Guttman, 1998; Sims et al., 2002). In this study, we applied the commonly used Standardized Precipitation Index (SPI) (McKee et al., 1993) and Standardized Runoff Index (SRI) (Shukla and Wood, 2008) to analyse meteorological droughts and hydrological droughts, respectively. Both SPI and SRI can be expressed on different time scales, e.g. 3 months, 6 months and 12 months. Table 2 shows how an event can be classified according to the SPI and SRI values.

First, we calculated 12-month SPI for 17 precipitation stations and 12-month SRI for 12 discharge stations for the period from 1940 to 2011. Then, for each severe drought with SPI or SRI values -1.5 or below, we determined severity and intensity of both meteorological and hydrological droughts. A threshold value of -1 (SPI or SRI) was used to define a drought event (beginning and ending of a drought).

From the drought severity calculated for each rainfall station, we derived average severity of meteorological drought for each sub-catchment based on the Thiessen polygons method. The hydrological drought severity for each sub-catchment corresponds to the drought severity of the discharge station at the outlet of that sub-catchment.

Furthermore, the most severe drought was selected to show the variability of the drought severity and intensity over the catchment. For this drought, the drought severity and intensity was determined for each precipitation station. Kriging interpolation (Matheron, 1963) was used to produce the meteorological drought severity contour map over the catchment.

**Water deficit during drought period**

For the water deficit computation, the catchment was divided into 7 main sub-catchments (see Figure 1). The water deficit per sub-catchment during a drought was computed as the water availability minus the water requirements. The water availability was considered to be the natural flow of the river computed by DWAF (2009) minus the stream flow reduction due to the forestry water use.
The main water requirements in the Crocodile catchment include irrigation, domestic and industrial supply, and a minimum transboundary flow, which is the agreed minimum discharge that has to be released to the Mozambican territory. Irrigation constitutes the principal water demand. Domestic and industrial water requirements were provided by DWAF (2009) study and the minimum transboundary flow of 0.9 m$^3$/s was obtained from the Water Use Agreement signed between Mozambique, Swaziland and South Africa (TPTC, 2002). Irrigation water requirements were computed based on the FAO’s recommendations (FAO, 1997). The effective precipitation, i.e. the precipitation available in the soil for the plants, is one of the necessary components for the irrigation water requirements computation. We computed the effective precipitation based on a fixed percentage approach (Smith, 1988). It consists of determining the 80% probable rainfall (P$_{80}$) and correcting for possible outfluxes due to runoff and percolation. As the main focus of this paper is to compute the irrigation requirements for the worst drought, instead of using the P$_{80}$, the average observed precipitation during the drought period was used which is close to the P$_{70}$.

**Groundwater modelling to develop a drought mitigation strategy**

A numerical groundwater model was constructed to assess groundwater potential during the drought period and to simulate the impacts of groundwater abstraction on the storage, water levels and base flow reduction in the river. The most severe drought observed within the study period was selected. The groundwater model is based on the widely used modelling software MODFLOW (McDonald and Harbaugh, 1983). First, a steady state model was constructed, with the objective of determining the initial conditions for the transient model. Second, a simplified transient natural model was built with recharge on a monthly scale representing the average monthly recharge for the drought period. The model consists of one layer representing the weathered and fractured rocks. A model grid cell of 1x1 km$^2$ was used, in line with the course spatial data sets available. The river catchment boundary was defined as the model boundary, given the fact that the shallow groundwater flow is mainly discharged to the rivers in the catchment.

Initial values of the recharge to the groundwater from the sub-catchments were computed by using the Thorntwaite water balance model from the U.S. Geological Survey (McCabe and Markstrom, 2007). The water balance model was calibrated using the available river discharge data from several sub-catchments.

The MODFLOW Evaporation package parameters were determined for each sub-catchment. The evaporation surface is the same as surface elevation of the catchment. An extinction depth of 5 m, the average root depth of pine and eucalypt trees (Alliance, 2002), was assigned for the forestry dominated
sub-catchments, namely: Nelpsruit, White River, Elands and Kaap sub-catchments; the depth of 2 m, the average root depth of grass roots under semi-arid conditions (Murphy, 2010) was assigned for Kwena, Middle Crocodile and Lower Crocodile sub-catchments which are mainly covered by savannas. The reference evaporation provided by DWAF (2009) is assigned as the maximum rate of evaporation. The River package was used to simulate groundwater discharges to rivers as base flow. Finally, the model was calibrated in the steady state manually to adjust the groundwater recharge using the available observed groundwater levels and the river discharges.

2.4. Scenarios using groundwater as an emergency source

As the objective here is to use the groundwater only as an emergency source, the existing drought mitigation strategy of the catchment was taken into account for the computation of the groundwater abstraction needs. The existing drought mitigation strategy comprises the storage of surplus water (during the wet season) in dams and water transfers within the catchment and from out of the catchment (Table 3). Only the storage of the major dams (storage capacity > 1.0M m$^3$) are considered, these dams are Kwena, Klipkopje, Longmere and Primkop dams with full storage capacities of 158.9Mm$^3$, 11.9Mm$^3$, 4.3Mm$^3$ and 2Mm$^3$, respectively.

It was assumed that the surplus water of the wet season will be stored in dams and further used in the dry period (useful water surplus - UWS). This useful water surplus was obtained by subtracting evaporation from the dams from the water surplus and applying a reduction factor of 0.7 to take into account the losses in the river channel. Thus, for each sub-catchment, the groundwater abstraction need was computed using equation:

$$GWN = WD_i - UWS + T_{out} - T_{in}$$  \hspace{1cm} (2.1)

GWN - groundwater abstraction need (Mm$^3$/yr);
WD$_i$ - initial water deficit (Mm$^3$/yr);
UWS - useful water surplus (Mm$^3$/yr);
T$_{out}$ - the water transferred out of the catchment (Mm$^3$/yr); and
T$_{in}$ - the water transferred in to the catchment (Mm$^3$/yr).

The water to be abstracted from the groundwater per sub-catchment corresponds to the groundwater abstraction needs. Based on the amount of groundwater abstraction needs, a number of wells were placed over the sub-catchments based on the topography, places near cities and irrigation areas were also a target for the well locations. Rock formations with higher borehole yield were also used as a criterion for the well locations; however, in many cases it was not possible to avoid placing wells in low borehole yield...
regions as these were found to be the most dominant formation in the sub-catchment, for instance, the White River. Then model simulations were performed to test whether the amounts of water can be abstracted. Finally, for an extremely severe drought, more severe than the most severe drought registered in the last 50 years, model simulations were carried out for different scenarios. For such a severe drought precipitation would be less, consequently recharge would be reduced and water demand would be higher. Therefore, four simulation scenarios (Table 4) were proposed where baseline recharge (between 1992 and 1995) was reduced and well abstractions linearly increased. These scenarios of recharge values mimic extremely severe drought conditions.

3. Results and discussion

3.1. Results of drought classification

Drought classification over time
The results of the SPI and SRI of 12-month scale indicated that droughts occurred during 1966, 1978, 1983, 1992-1995, and 2003-2004 (Figure 3). In other words, in 50 years from 1960 to 2011, 6 droughts occurred. Results of the drought severity for Elands River sub-catchment (station X2H015) and Crocodile catchment outlet (X2H016) are shown in Figure 4 as examples.

Three severe droughts occurred in 1983, in 1992-1995, and in 2003-2004. These droughts were also noticed in most of South Africa and neighbouring countries. The most severe one was the 1992-1995 drought, it lasted for around 4 consecutive years. This drought can be classified as severely dry as a meteorological drought and extremely dry as a hydrological drought. It appears from Figure 4 that the severity of meteorological drought (SPI) used to be higher than the severity of the hydrological drought (SRI) before 1975. But after 1975 the hydrological drought severity is higher than the meteorological drought severity. This can be explained by the increasing abstractions of water from the rivers for agricultural, domestic and industrial consumption.

Drought classification over the catchment
Figure 5 presents the 1992-1995 meteorological drought severity over the Crocodile catchment. Figure 6 shows the variability of the drought index (SPI) during the drought duration over the catchment. The plot shows for each station the minimum, maximum, standard deviation and average SPI (drought intensity) during 1992-1995.

The more severe droughts occur in the upstream and downstream areas of the catchment while the middle part of the catchment presents low drought severity. Similarly, the upstream and downstream precipitation stations present high variability of the drought index reaching very high and very low values of SPI. The
maximum value of SPI reached in this drought was -5.5 in two stations upstream and one station in downstream. On the other hand, the stations in the middle part of the catchment present less variability of SPI during the drought duration where the maximum value of SPI was around -2.5.

The variation of the hydrological drought severity for each sub-catchment is shown in Figure 7. Figure 8 shows the variability of the hydrological drought index during the drought duration over the entire catchment; it follows the same spatial pattern of variation as for the meteorological drought intensity presented in Figure 5.

The hydrological drought severity does not depend only on amount of rainfall; it was also affected by the amount of water abstracted from the river. Therefore, sub-catchments with less rainfall and high water requirements are the most affected by droughts. For instance, the Kaap catchment (gauging station X2H022) and the Lower Crocodile catchments (gauging station X2H016), which are located in low rainfall regions and have very high water requirements, are the most vulnerable to droughts and present high drought severity, -90.7 and -103.1 for the Lower Crocodile and Kaap, respectively. On the other hand, the Kwena sub-catchment is the less affected by the hydrological drought, the hydrological drought severity is around -22.4. It has less water requirements, in addition its discharge station (X2H070) is located downstream of the major dam of the Crocodile River (the Kwena dam). Therefore, the dam's operation to keep the flows in regulated levels together with the low water requirements contributes significantly to its low vulnerability to droughts.

The hydrological drought severity on the other small upstream catchments, such as stations X2H012, X2H008, X2H068 are more dependent on precipitation. On the other hand, the severity on the downstream stations which drain bigger areas (X2H015, X2H022, X2H016) are not only affected by precipitation but also highly affected by the increased water abstraction from the river for irrigation, domestic and industrial use, thus presenting very high values of hydrological drought severity. Accordingly, most upstream discharge stations have less variability on the SRI, and the downstream stations present high variability of SRI and higher drought intensity. The maximum SRI reached by most upstream sub-catchments is -2.1 and the maximum SRI reached by the downstream stations is -3.2. It seems like the sub-catchment water transfers does not influence much on the drought severity.

3.2. Water deficit and groundwater abstraction

The total water available versus water demand in the whole catchment since 1960 is presented in Figure 9. The total irrigated area in the Crocodile River catchment is 466.5 km² which correspond to around 4.5%
of the catchment. The main crops are the sugarcane, vegetables and citrus occupying about 44%, 31% and 20% of the total irrigated area, respectively. The remaining 5% is occupied by maize which is mostly cultivated in the upper region. Results of the irrigation water requirements per sub-catchment are presented in Table 5. The sub-catchment which presents the highest demand in terms of irrigation is the Lower Crocodile; it demands around 50% of the total irrigation requirements in the catchment and it is part of the driest area of the catchment. The variation of the irrigation water demand over the year (Figure 8) does not change according to the season, as it depends on many factors, mainly precipitation, evaporation and crop type. The crop factor varies with the crop type, cropping pattern and plant development, for instance, the vegetables are only planted in winter (between March and August) thus requiring water only in this period, while sugar cane exists in the whole year but requires more water during the hot season. Therefore, there is no correlation with evaporation or temperature for the total irrigation water demands. However, it can be noted that despite the low evaporation between April and September, the average irrigation water requirement during this period is slightly higher than the irrigation average water requirement during October and March. This is mainly due to the low precipitation in this period that coincides with the low temperature season.

The annual domestic and industrial water requirements in the Crocodile catchment are 95 Mm$^3$/yr and 22.4 Mm$^3$/yr, respectively, (DWAF, 2009). The Water Use Agreement (TPTC, 2002) signed between Mozambique, South Africa and Swaziland stipulated that the Incomati River should maintain a minimum flow of 2.6 m$^3$/s average of a 3 days period in Ressano Garcia (in Mozambique). Thus, they recommended that a minimum of 1.2 m$^3$/s should be maintained by the Crocodile River and 1.4 m$^3$/s should be maintained by the Komati River system. The annual water requirements for domestic and industrial supply were distributed equally per month and per sub-catchment. The transboundary flow requirement was distributed per sub-catchment based on the percent distribution of annual discharge of each sub-catchment and further distributed equally per month.

Results of the water deficit computation (Table 5) show that the most stressed sub-catchments are those located in the downstream area where precipitation is lower, evapotranspiration is higher and have higher irrigation water demand. The upper catchments Kwena and Elands did not present any water deficit in this period due to low water requirements. The total water deficit of the catchment, in the drought period, is estimated to be to 159.8 Mm$^3$/yr.

A water surplus in the wet season of around 57.1 Mm$^3$/yr was obtained for the Kwena and White River catchments. Results show that, the use of the existing drought mitigation plan (see Table 3), roughly, would reduce the water deficit from 159.8 Mm$^3$ to 97 Mm$^3$, a reduction of 40%. This shows the critical
importance of using an additional source of water to cope with this hazard - a key role that groundwater resources could play. The groundwater requirements for combating drought are listed in Table 5.

3.3. Results of groundwater modelling
The calibration of the steady groundwater flow model resulted in a good agreement between measured and computed groundwater levels with $R^2$ of 0.96 and Nash Sutcliffe efficiency of 0.97 (Figure 10). The simulated base flow per sub-catchment fits the observed base flow (Table 6), baseflow was separated using the HYSEP software (Sloto and Crouse, 1996). The net recharge represents the actual recharge; it is the recharge from precipitation plus the river leakage into the groundwater storage minus the evaporation from the groundwater storage. During the drought period the total net recharge for the whole catchment was found to be 529 Mm$^3$/yr which correspond to 50 mm/yr, around 8% of the total annual precipitation during the drought. According to the groundwater study which covers the Crocodile area (WRC, 2005), the long term annual average recharge in the Crocodile catchment is around 77.9 mm/yr which correspond to 9% of the long-term average rainfall in the region. Thus, the percentage of recharge from precipitation of this research and the (WRC, 2005) study are very close.

The calculated groundwater level contour lines generally follow the topography of the catchment. Groundwater level is deeper in the high mountains within the catchment and shallower in plane areas as the downstream region. The river is mainly fed by the aquifer, only in few areas as in the higher mountains the aquifer is fed by the river. Water budget results show that the principal input of water in the groundwater storage is the recharge from precipitation (479.52 Mm$^3$/yr). Evaporation from the groundwater storage (120.26 Mm$^3$/yr) is low compared to the recharge given the fact that the groundwater table is deep (> 5 m) in many parts of the catchment.

4. Feasibility of using groundwater as an emergency source
Transient abstraction simulations were performed by assigning well abstraction rates equal to the groundwater abstraction needs per sub-catchment listed in Table 5 and showing in Figure 11. Results show that if 97 Mm$^3$ of water is abstracted per year, then river base flow for the whole catchment would reduce only by 3.1% (16.51 Mm$^3$/yr), meaning that it is possible to use the groundwater as an emergency source for drought mitigation. However, looking at the results in a sub-catchment scale, the most affected
sub-catchments in terms of reduction of base flow, as expected, are the drier sub-catchments: White River, Kaap and Lower Crocodile. The most affected is the White River with a base flow reduction of 18%. The other catchments present a base flow reduction of around 8%. However, it is still feasible to abstract water in these sub-catchments. The groundwater levels in Kwena and Elands sub-catchments do not change because there are no abstractions in these sub-catchments while a maximum water table drawdown of around 4m can be observed in the other catchments where there are abstractions, except for White River catchment where drawdown reach values of around 20m.

4.2. Use of groundwater in case of extremely severe drought

Four scenarios of using groundwater in case of extremely severe drought proposed in Table 4 were simulated with the transient groundwater flow model. The model simulation period consists of 4 drought years (taking 1992-1995 drought as reference) followed by 11 normal years. Groundwater is abstracted during the drought years, but switched off during the normal years. The monthly stress period is used to consider seasonal variation of groundwater recharge. Model simulation results were analysed for the maximum drawdown and reduction of base flow and compared the natural groundwater flow model, a model where abstraction wells are not taken into account. For the simulation scenario 1, the base flow reduction is low, it varies between 2.4% to 8.6% for the sub-catchments, except in White River where base flow reduction is around 18%. In the most extreme situation of simulation scenario 4, base flow reduction is higher: 12.2%, 12.5%, 20.1%, 11.3% and 21.1% in Kwena, Elands, Kaap, Middle Crocodile and Lower Crocodile, respectively. And even much higher in the White River and Nelspruit sub-catchments where the base flow reduction is 28.8% and 58.6%, respectively. Figure 12 shows the decrease of groundwater levels for the observation wells located in White River as example. A maximum drawdown of 1.2m, 3.5m and 10m was observed after 3 years in Kwena, Elands and Kaap sub-catchments, respectively, in the simulation scenario 4. However, in sub-catchments White River and Nelspruit the drawdowns are very high, and the worse case is the White River. The drawdowns reach values of 28m, 36m and 49m in simulation scenarios 2, 3 and 4, respectively after 3 year of abstractions. This happens due to the fact that these two sub-catchments are mainly constituted by intergranular and fractured aquifer type with low permeability. This high drawdown besides affecting the agricultural activity causes a decrease in the river flows, thus reducing the water availability to less than 50% in simulation scenario 4 for the White River catchment (see Figure 13). Briefly, results of the abstraction simulations for the different scenarios show that in most of the sub-catchments it is possible to use the groundwater water for drought mitigation in case of extremely severe droughts. Groundwater levels would recover back to pre-drought situation when emergency wells are switched off after the drought.
However, groundwater exploitation in White River and Nelspruit sub-catchments is limited due to very high drawdowns and, consequently, high river flow reduction during the drought.

5. Conclusions

Several severe droughts occurred in the Crocodile catchment over more than 50 years from 1960 to 2011. The most severe drought was the 1992-1995 drought. There are spatial differences in drought severity and intensity. The lower and upper catchments show high meteorological drought severity, while the middle catchment shows low meteorological drought severity. The hydrological drought severity doesn't only affect by meteorological drought, but also affected by the human interventions on the catchment. Thus, the hydrological drought severity is higher in the most water stressed sub-catchments, such as the Kaap and Lower Crocodile and is lower in the less water stressed catchments such as Kwena where the flows are regulated by the Kwena dam reducing the severity of droughts. It was found that before 1975's the meteorological drought severity was higher than the hydrological drought severity. On the contrary, after 1975's the hydrological drought severity is higher than the meteorological drought severity. This shift could be due to increased water consumption in the catchment by forestry, irrigation and domestic use over time.

The water balance study of the catchment shows that the total water deficit during a severe drought (such as 1992-1995 drought) amounts up to 159.8 Mm$^3$/yr, and the most stressed sub-catchments are the Lower Crocodile, Kaap, White River, Nelspruit and Middle Crocodile. Taking into account the existing drought mitigation plan (water storage and inter-basin transfers) this water deficit reduces only by about 40% to 97Mm$^3$/yr. This shows that it is important to consider the use of groundwater to mitigate the droughts. Groundwater abstraction simulation reveals that it is possible to use the groundwater as an emergency source of water to mitigate the drought hazards in the Crocodile River catchment. In general, the Kaap, Middle Crocodile and Lower Crocodile sub-catchments are most feasible for groundwater exploitation while the groundwater exploitation in Nelspruit and White River catchments is restricted due to high river flow reduction and high drawdown during the drought.

This case study demonstrates that conjunctive water management of groundwater and surface water resources is necessary to mitigate the impacts of droughts. This needs a multi-methods approach including coupled modelling of surface water and groundwater fluxes, where the detailed geological features of the study area are taken into account, as well as a long time series of groundwater levels are crucial for the good model calibration.
Acknowledgements

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<th>Precipitation stations</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td>Station name</td>
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<td>End year</td>
<td>% of missing data</td>
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<td>1940</td>
<td>2000</td>
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<td>1940</td>
<td>2000</td>
<td>3.3</td>
</tr>
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<td>Rietvallei</td>
<td>0555441 W</td>
<td>1940</td>
<td>2001</td>
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<tr>
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<td>Dullstroom</td>
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<td>Mayfern</td>
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<td>Weltevreden</td>
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<td>Riverside</td>
<td>0557115 W</td>
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<td>Witklip</td>
<td>0555673 W</td>
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<tr>
<td>Malelane</td>
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<td>1940</td>
<td>2000</td>
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<td>Krokdilbrug</td>
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<td>Uitsoek</td>
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<th>Discharge stations</th>
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<td>Sassenheim</td>
<td>X2H008</td>
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<td>Bellevue</td>
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<td>Ten Bosch</td>
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<td>Dolton</td>
<td>X2H022</td>
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<td>2012</td>
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<td>Bornmans Drift</td>
<td>X2H031</td>
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<td>2012</td>
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<td>Witklip Dam</td>
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<td>1969</td>
<td>2012</td>
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<td>Kwena Dam</td>
<td>X2H070</td>
<td>1979</td>
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### Table 2 - SPI or SRI classes

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<tr>
<th>SPI or SRI range</th>
<th>Classification</th>
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<tr>
<td>SPI or SRI ≤ -2.0</td>
<td>Extremely dry</td>
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<tr>
<td>-2.0 &lt; SPI or SRI ≤ -1.5</td>
<td>Severely dry</td>
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<tr>
<td>-1.5 &lt; SPI or SRI ≤ -1.0</td>
<td>Moderately dry</td>
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<tr>
<td>-1.0 &lt; SPI or SRI ≤ 1.0</td>
<td>Near normal</td>
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<tr>
<td>1.0 &lt; SPI or SRI ≤ 1.5</td>
<td>Moderately wet</td>
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<tr>
<td>1.5 &lt; SPI or SRI ≤ 2.0</td>
<td>Severely wet</td>
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<tr>
<td>SPI or SRI ≥ 2.0</td>
<td>Extremely wet</td>
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</table>

Source: (Sienz and Jahnke-Bornemann, 2012)
### Table 3 - Water transfer in the Crocodile catchment

<table>
<thead>
<tr>
<th>Transfer from</th>
<th>Transfer to</th>
<th>Amount transfer (Mm³/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nelspruit</td>
<td>White River</td>
<td>3.0</td>
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<tr>
<td>(*) Sabie and Lomati</td>
<td>Kaap</td>
<td>8.5</td>
</tr>
<tr>
<td>Middle Crocodile</td>
<td>Lower Crocodile</td>
<td>25.6</td>
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<tr>
<td>(*) Sabie and Lomati</td>
<td>Lower Crocodile</td>
<td>6.0</td>
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</table>

Source: (DWAF, 2009), (*) Outside the Crocodile

### Table 4 - Abstractions simulation scenarios

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Recharge</th>
<th>Wells abstraction</th>
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<tbody>
<tr>
<td>Simulation 1</td>
<td>Reduced in 10%</td>
<td>Increased in 10%</td>
</tr>
<tr>
<td>Simulation 2</td>
<td>Reduced in 25%</td>
<td>Increased in 25%</td>
</tr>
<tr>
<td>Simulation 3</td>
<td>Reduced in 50%</td>
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<tr>
<td>Simulation 4</td>
<td>Reduced in 50%</td>
<td>Increased in 100%</td>
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</table>
Table 5 - Irrigation water requirements and water deficit per sub-catchment for the 1992-1995 drought

<table>
<thead>
<tr>
<th>Sub-catchment</th>
<th>Irrigation requirements (Mm$^3$/yr)</th>
<th>Water deficit before applying existing drought mitigation plan (Mm$^3$/yr)</th>
<th>GW abstraction needs after applying existing drought mitigation plan (Mm$^3$/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kwena</td>
<td>6.43</td>
<td>0</td>
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<tr>
<td>Elands</td>
<td>12.47</td>
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<td>Nelspruit</td>
<td>22.83</td>
<td>-8.1</td>
<td>11.0</td>
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<td>White River</td>
<td>17.58</td>
<td>-35.5</td>
<td>27.0</td>
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<tr>
<td>Kaap</td>
<td>80.3</td>
<td>-12.8</td>
<td>24.0</td>
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<tr>
<td>Middle Crocodile</td>
<td>55.18</td>
<td>-15.4</td>
<td>10.4</td>
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<tr>
<td>Lower Crocodile</td>
<td>196.48</td>
<td>-88</td>
<td>24.6</td>
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<tr>
<td>Whole catchment</td>
<td>391.27</td>
<td>-159.8</td>
<td>97.0</td>
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</table>

Table 6 - Groundwater model calibration results

<table>
<thead>
<tr>
<th></th>
<th>Recharge (Mm$^3$/yr)</th>
<th>Net recharge (Mm$^3$/yr)</th>
<th>Simulated base flow (Mm$^3$/yr)</th>
<th>Observed base flow (Mm$^3$/yr)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kwena</td>
<td>97.15</td>
<td>99.39</td>
<td>55.74</td>
<td>54.97</td>
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<tr>
<td>Elands</td>
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<td>162.90</td>
<td>127.25</td>
<td>126.18</td>
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<tr>
<td>Nelspruit</td>
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<td>102.45</td>
<td>45.09</td>
<td>45.19</td>
<td>-0.2%</td>
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<td>White River</td>
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<td>Kaap</td>
<td>21.80</td>
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<tr>
<td>Middle Crocodile</td>
<td>68.67</td>
<td>66.85</td>
<td>196.43</td>
<td>197.90</td>
<td>-0.7%</td>
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<tr>
<td>Lower Crocodile</td>
<td>21.98</td>
<td>18.67</td>
<td>32.87</td>
<td>32.56</td>
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<tr>
<td>Whole catchment</td>
<td>477.07</td>
<td>529.01</td>
<td>528.59</td>
<td>528.04</td>
<td>0.1%</td>
</tr>
</tbody>
</table>
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Figure 2 Research methodology

- Identification of severe droughts
- Determination of water deficit during the drought
- Assessment of groundwater resources
- Drought mitigation scenarios

Objectives

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Results</th>
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<tbody>
<tr>
<td>- Standardized Precipitation Index (SPI)</td>
<td>- Temporal changes of drought severity</td>
</tr>
<tr>
<td>- Standardized Runoff Index (SRI)</td>
<td>- Spatial distribution of drought severity</td>
</tr>
<tr>
<td>- Computation of drought severity and intensity</td>
<td>- Drought severity per sub-catchments</td>
</tr>
<tr>
<td>- Water balance method</td>
<td>- Water deficit per sub-catchments</td>
</tr>
<tr>
<td>- Water deficit = water availability – water demand</td>
<td>- Groundwater requirement per sub-catchments</td>
</tr>
<tr>
<td>- Construction and calibration of steady groundwater flow model</td>
<td>- Groundwater recharge</td>
</tr>
<tr>
<td>- Construction of transient groundwater flow model</td>
<td>- Baseflow</td>
</tr>
<tr>
<td>- Simulation of drought mitigation scenarios</td>
<td>- Feasibility of using groundwater for mitigating extreme droughts</td>
</tr>
</tbody>
</table>

Figure 3 Average SPI and SRI (12 month scale)
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