Hydrol. Earth Syst. Sci. Discuss., 11, 2719–2757, 2014
www.hydrol-earth-syst-sci-discuss.net/11/2719/2014/
doi:10.5194/hessd-11-2719-2014

Hydrology and Earth System Sciences
Open Access
Discussions

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

F. E. F. Mussá[1,2], Y. Zhou[1], S. Maskey[1], I. Masih[1], and S. Uhlenbrook[1,3]

[1]UNESCO-IHE, Institute for Water Education, P.O. Box 3015, 2601 DA Delft, the Netherlands
[2]Eduardo Mondlane University, Faculty of Engineering, Av. de Moçambique km 1.5, C. Postal 257, Maputo, Mozambique
[3]Delft University of Technology, Section of Water Resources, P.O. Box 5048, 2600 GA Delft, the Netherlands

Received: 31 January 2014 – Accepted: 12 February 2014 – Published: 6 March 2014

Correspondence to: F. E. F. Mussá (mussa2@unesco-ihe.org)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Global climate change has received much attention worldwide in the scientific as well as in the political community, 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 supplement 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 meteorological drought severity varies accordingly with the precipitation; 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 those which are more vulnerable to severe hydrological droughts. The analysis of the potential groundwater use during droughts showed that a deficit of 97 $Mm^3 yr^{-1}$ 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 supplement 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.

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

HESSD
11, 2719–2757, 2014

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, 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 (van der 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

HESSD
11, 2719–2757, 2014

adjacent catchments (Sabie 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 vs. 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 2030 m in the most upstream part and gradually decreasing to 140 m at the outlet (Fig. 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 2452 km^2 in 2004 which corresponds to around 61 % of the total irrigated area in the whole Incomati catchment.

HESSD
11, 2719–2757, 2014
Groundwater as an emergency source for drought mitigation, South Africa
F. E. F. Mussá et al.

The catchment is characterised by semi-arid climate with an annual rainfall and potential evaporation of 850 and 1380 $mm\,yr^{-1}$, 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 in-filled 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 for each station the percentage of reliability, which represents the percentage of observed or original data of the time series.

Data from this database was used and from 2001 onwards, data provided only by SAWS was used. 17 precipitation stations with high percentage of reliability (Table 1)

HESSD
11, 2719–2757, 2014

and a good spatial variability (Fig. 1) were selected. The time cover for reliable 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 year of data), gaps on the time series (Table 1) and spatial variability of the stations (Fig. 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 and the Lower Crocodile is even scarcer in terms of wells and well data. Thus, only 10 wells with water level measurements during drought periods were available for the model calibration (Fig. 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 $90 \times 90\,m^2$ 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 Fig. 1). Aquifer parameters such as layers thickness and hydraulic conductivity are those presented in 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 Fig. 2. The methodology consists of drought classification, water deficit assessment during drought periods, and groundwater modelling for analysing groundwater potential for drought mitigation.

HESSD
11, 2719–2757, 2014

2.3.1 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, 6 and 12 months. Table 2 shows how an event can be classified according to the SPI and SRI values.

First, we calculated SPI for 17 precipitation stations and SRI for 12 discharge stations for the period from 1940 to 2011. Then, for each severe drought with SPI or SRI values of −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

HESSD
11, 2719–2757, 2014

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.

2.3.2 Water deficit during drought period

For the water deficit computation, the catchment was divided into 7 main sub-catchments (see Fig. 1). Then, the water deficit per sub-catchment was computed as the water availability minus the water requirements. The water deficit was computed for the most severe drought occurred during 1940 to 2011. Therefore, 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 area presented by the same study.

The main water uses 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 obtained from the DWAF (2009) study and the minimum transboundary flow of 0.9 $m^3 s^{-1}$ 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

HESSD
11, 2719–2757, 2014

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}.

2.3.3 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 $1 \times 1\,km^2$ was selected, 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 US 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 obtained from (DWAF, 2009) study is

HESSD
11, 2719–2757, 2014

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 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 Mm^3) are considered, which drains a large area (> 65 % of the sub-catchment area) were taken into account, These areas are Kwena, Klipkopje, Longmere and Primkop dams with full storage capacities of 158.9, 11.9, 4.3 and 2 Mm^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:

$$\mathrm{GWN} = \mathrm{WD_i} - \mathrm{UWS} + T_{\mathrm{out}} - T_{\mathrm{in}} \quad (1)$$

GWN – groundwater abstraction need ($Mm^3\,yr^{-1}$);
WD_i – initial water deficit ($Mm^3\,yr^{-1}$);
UWS – useful water surplus ($Mm^3\,yr^{-1}$);
T_{out} – transfer out ($Mm^3\,yr^{-1}$); and
T_{in} – transfer in ($Mm^3\,yr^{-1}$).

HESSD
11, 2719–2757, 2014

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 70 year, 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

3.1.1 Drought classification over time

The results of the SPI and SRI of 12 month scale indicated that severe droughts occurred during 1945, 1951, 1958, 1966, 1970/71, 1978, 1983/84, 1992 to 1995, and 2003/04. In other words, in 70 years from 1940 to 2011, 9 severe droughts occurred of which 5 of them occurred before 1975, the middle year of the observations, and 4 after 1975. However, the most severe ones occurred after 1975. Results of the drought

HESSD
11, 2719–2757, 2014

severity for Elands River sub-catchment (station X2H015) and Crocodile catchment outlet (X2H016) are shown in Fig. 3 as examples.

The most severe droughts occurred in 1983, from 1992 to 1995 and in 2003/04. 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 with severity of −90 and intensity of −2.02 on the hydrological drought and severity of −65 and intensity of −1.67 on the meteorological drought (Fig. 3). This drought can be classified as severely dry as a meteorological drought and extremely dry as a hydrological drought. It appears from the graphs 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.

3.1.2 Drought classification over the catchment

Figure 4 presents the 1992–1995 meteorological drought severity over the Crocodile catchment. Figure 5 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 meteorological drought severity follows more or less the same pattern as the precipitation (see Fig. 4), where more severe droughts occur in the upstream and downstream areas of the catchment while the middle part of the catchment characterized by higher precipitation 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

HESSD
11, 2719–2757, 2014

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 Fig. 6. Figure 7 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 Fig. 4.

The hydrological drought severity does not depend only on amount of rainfall; it was also affected by the amount of water that was 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 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 dependent on precipitation, they are 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, the 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 the most upstream sub-catchments is −2.1 and the maximum SRI reached

HESSD
11, 2719–2757, 2014

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 during drought periods

3.2.1 Water deficit

Water deficit was computed for the most severe drought period 1992/95. The total irrigated area in the Crocodile River catchment is 466.5 km^2 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 (Fig. 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 and 22.4 $Mm^3 yr^{-1}$, respectively, (DWAF, 2009). The Water Use Agreement (TPTC, 2002) signed between Mozambique, South Africa and Swaziland stipulated

HESSD
11, 2719–2757, 2014

that the Incomati River should maintain a minimum flow of 2.6 $m^3 s^{-1}$ average of a 3 days period in Ressano Garcia (in Mozambique). Thus, they recommended that a minimum of 1.2 $m^3 s^{-1}$ should be maintained by the Crocodile River and 1.4 $m^3 s^{-1}$ 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 $Mm^3 yr^{-1}$.

3.2.2 Groundwater abstraction needs

A water surplus in the wet season of around 57.1 $Mm^3 yr^{-1}$ 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 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

Steady-state model application

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

HESSD
11, 2719–2757, 2014

Sutcliffe efficiency of 0.97. The simulated base flow per sub-catchment fits the observed base flow. 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 $Mm^3 yr^{-1}$ which correspond to 50 $mm yr^{-1}$, 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 $mm yr^{-1}$ 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 difference between simulated and observed flows is on average 0.1 %, and varies between −0.2 and 1.4 %.

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 $Mm^3 yr^{-1}$). Evaporation from the groundwater storage (120.26 $Mm^3 yr^{-1}$) 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

4.1 Use of groundwater in a drought period (1992–1995 drought)

Transient abstraction simulations were performed by assigning well abstraction rates equal to the groundwater abstraction needs per sub-catchment listed in Table 5. 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 $Mm^3 yr^{-1}$), meaning that it

HESSD
11, 2719–2757, 2014

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 4 m can be observed in the other catchments where there are abstractions, except for White River catchment where drawdown reaches values of around 20 m.

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, a model where recharge varies seasonally. The simulation period was 3 years with monthly stress period considering the longest consecutive drought in the history (1992–1995 drought). 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 9 shows the decrease of groundwater levels for the observation wells located in White River and Kaap catchments as examples. A maximum drawdown of 1.2, 3.5 and 10 m was observed after 3 years in Kwena, Elands and Kaap sub-catchments, respectively, in the simulation scenario 4 (see Fig. 10). 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 28, 36 and 49 m 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 Fig. 11). 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. However, groundwater exploitation in White River and Nelspruit sub-catchments is limited due to very high drawdowns and, consequently, high river flow reduction.

5 Conclusions

Several severe droughts occurred in the Crocodile catchment over more than 70 years from 1940 to 2011. In general, it was found that the spatial variability of the meteorological drought severity follows the same pattern as the precipitation. For instance, the lower and upper catchments characterized by lower precipitation show high meteorological drought severity, while the middle catchment characterized by high precipitation shows low meteorological drought severity. However, the hydrological drought severity does not follow exactly the same pattern as the metrological drought severity, because besides precipitation it is 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. Regarding the drought severity over time, it was noted that before 1975's the meteorological drought severity was higher than the hydrological drought severity. On the contrary, after 1975's the hydrological

HESSD
11, 2719–2757, 2014

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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 period (such as 1992–1995 drought) amounts up to 159.8 $Mm^3 yr^{-1}$, 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 97 $Mm^3 yr^{-1}$. 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 drawdowns.

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. We gratefully acknowledge the partial funding for the field research and paper writing provided through the RISKOMAN and the RISKOMAN-GAM projects funded by DGIS/UNESCO-IHE Programmatic Cooperation (DUPC). The additional support for preparing this manuscript from DEWFORA project which is funded by the Seventh Framework Programme for Research and Technological Development (FP7) of the European Union (Grant agreement no: 265454) is also thankfully acknowledged. We are also very grateful to the groundwater department of DWAF (Department of Water Affairs and Forestry), SAWS (South African Weather Service) and ICMA (Incomati Catchment Management Agency) in South Africa for the data provided.

References

Alliance, T. L.: Longleaf pine root system, available at: http://www.longleafalliance.org/longleaf-pine/physiology/longleaf-pine-roots/?searchterm=pine%20tree, last access: 15 December 2012, 2002.

Baron, J., Seward, P., and Seymour, A.: The Groundwater Harvest Potential Map of the Republic of South Africa, Department of Water Affairs and Forestry, Pretoria, Gh 3917, 1998.

Baykan, N. O. and Özçelik, C.: Management of drought, Water resources management: Risks and Challenges for the 21st century, E.W. Publications, Turkey, 2006

Climate indices: available at: http://icdc.zmaw.de/climate_indices.html?&L=1 (last access: 10 September 2012), 2012.

DWA: Water Requirements and Availability Reconciliation Strategy for the Mbombela Municipal Area, Department of Water Affairs, Pretoria, South Africa, 2013.

DWAF: Groundwater Resources Assessment II – Recharge Final Report, Department of Water Affairs and Forestry, Pretoria, South Africa, 2006.

DWAF: Hydrology of the Crocodile River, PWMA 05/X22/00/1508, Department of Water Affairs and Forestry, Pretoria, South Africa, 2009.

FAO: FAO Land and Water Bulletin, Rome, 1997.

Fischer, S., Witthüser, K., Birke, M., Leyland, R., and Schneider, M.: Regional description of the groundwater chemistry of the Kruger National Park (KNP) using multivariate statistics, Groundwater Conference 2009, Somerset West, South Africa, 2009.

Fischer, S., Witthüser, K., Birke, M., Leyland, R., and Schneider, M.: Describing the groundwater system of the Kruger National Park (South Africa) on the basis of hydrogeochemical methods and multivariate statistical algorithms, FH-DGG Tübingen, Schriftenreihe der Deutschen Gesellschaft für Geowissenschaften, Germany, 2010..

Fundisi, D., Riddell, E. S., and Lorentz, S. A.: Hydrological Connectivity in Selected Pristine Catchments in the Kruger National Park, 16th SANCIAHS National Hydrology Symposium University of Pretoria, Pretoria, South Africa, 2012.

Guttman, N. B.: Comparing the Palmer Drought Index and the Standardized Precipitation Index, J. Am. Water Resour. As., 34, 113–121, doi:10.1111/j.1752-1688.1998.tb05964.x, 1998.

Leyland, R. C. and Witthüser, K. T.: Regional Description of the Groundwater Chemistry of the Kruger National Park, Water Research Commission, Pretoria, South Africa, 2008.

Loucks, D. and Beek, E. v.: Water Resources Systems Planning and Management – an Introduction to Methods, Models and Aplications, United Nations Educational, Unesco-IHE, Paris, 2005.
Lynch, S. D.: Development of a raster database of annual, monthly and daily rainfall for Southern Africa, Water Research Commision, Pretoria, South Africa, WRC Report 1156/1/04, 78 pp., 2003.
MacDonald, G. M.: Severe and sustained drought in southern California and the West: present conditions and insights from the past on causes and impacts, Quatern. Int., 173, 87–100, doi:10.1016/j.quaint.2007.03.012, 2007.
Management, W. S.: Water Resources Situation Assessment: Ground Water Resources of South Africa, Department of Water Affairs and Forestry, Pretoria, 2001.
Matheron, G.: Principles of geostatistics, Econ. Geol., 58, 1246–1266, 1963.
McCabe, G. J. and Markstrom, S. L.: A Monthly Water-Balance Model Driven By a Graphical User Interface, US Geological Survey open file report 2007-1088, Reston, Virginia, 2007.
McDonald, M. G. and Harbaugh, A. W.: A Modular Three-Dimensional Finite Difference Groundwater Flow Model, US Geological Survey, Denver, Colorado, 83–875, 1983.
McKee, T. B., Doesken, N. J., and Kleist, J.: The relation of drought frequency and duration to time scales, Eighth Conference on Applied Climatology, Anaheim, California, 1993.
Mishra, A. K. and Singh, V. P.: A review of drought concepts, J. Hydrol., 391, 202–216, doi:10.1016/j.jhydrol.2010.07.012, 2010.
Murphy, S. R.: Tropical perennial grasses – root depths, growth and water use efficiency Primefact, 2010.
Niekerk, A. V., Nel, J., and Riddell, E.: Conceptualizing groundwater distribution over different spatial and geological scales using electrical resistivity profiles within the Kruger National Park, 16th SANCHIAS National Hydrology Symposium University of Pretoria, Pretoria, South Africa, 2012.
Nonner, J. C.: Introduction to hydrogeology, CRC Press, Taylor and Francis group, Leiden, the Netherlands, 2010.
Palmer, W.: Keeping Track of Crop Moisture Conditions, Nationwide: the New Crop Moisture Index, Weatherwise 21, 156–161, doi:10.1080/00431672.1968.9932814, 1968.
Pavelic, P., Srisuk, K., Saraphirom, P., Nadee, S., Pholkern, K., Chusanathas, S., Munyou, S., Tangsutthinon, T., Intarasut, T., and Smakhtin, V.: Balancing-out floods and droughts: opportunities to utilize floodwater harvesting and groundwater storage for agricultural

HESSD
11, 2719–2757, 2014

development in Thailand, J. Hydrol., 470–471, 55–64, doi:10.1016/j.jhydrol.2012.08.007, 2012.
Rockström, J.: Resilience building and water demand management for drought mitigation, Phys. Chem. Earth, 28, 869–877, doi:10.1016/j.pce.2003.08.009, 2003.
Shukla, S. and Wood, A. W.: Use of a standardized runoff index for characterizing hydrologic drought, Geophys. Res. Lett., 35, L02405, doi:10.1029/2007gl032487, 2008.
Sims, A. P., Niyogi, D. d. S., and Raman, S.: Adopting drought indices for estimating soil moisture: a North Carolina case study, Geophys. Res. Lett., 29, 24–31, 2002.
Tanner, A. and Mauritius, A.: Baseline Evaluation and Scoping Report, Progressive Realisations of the Incomaputo Agreement (PRIMA), IAAP 3:03C-2010, Moçambique, 2010.
TPTC: Interim IncoMaputo Water Use Agreement, Tripartite Permanent Technical Committee, South Africa, Mozambique and Swaziland, 2002.
Vegter, J. R.: Groundwater Resources of the Republic of South Africa – Sheet 1 and Sheet 2, Water Res., South Africa, 1995.
Werick, W. J., Willeke, G. E., Guttman, N. B., Hosking, J. R. M., and Wallis, J. R.: National drought atlas developed, EOS Trans. Am. Geophys. Union, 75, 89–90, doi:10.1029/94eo00706, 1994.
Willeke, G.: The National Drought Atlas, US Army Corps of Engineers, Water Resources Support Center, Institute for Water Resources, 1994.
WRC: Water Resources of South Africa, K5/1491, Water Research Comission, Pietermaritzburg, 2005.
van der Zaag, P. and Vaz, Á. C.: Sharing the Incomati waters: cooperation and competition in the balance, IWA Publishing 5, 349–368, 2003.
Zargar, A., Sadiq, R., Naser, B., and Khan, F. I.: A review of drought indices, Environ. Rev., 19, 333–349, doi:10.1139/a11-013, 2011.
Zhou, Y., Wang, L., Liu, J., and Ye, C.: Impacts of drought on groundwater depletion in the Beijing Plain, China, in: Climate Change Effects on Groundwater Resources: a Global Synthesis of Findings and Recommendations, edited by: Treidel, H., Martin-Bordes, J. L., and Gurdak, J. J., CRC Press, Hardback, 2011.

HESSD
11, 2719–2757, 2014

Groundwater as an emergency source for drought mitigation, South Africa

F. E. F. Mussá et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. List of used data sets.

Precipitation stations				
Station name	Station number	Start year	End year	% of missing data
Alkmaar	0555567 W	1940	2012	0.0
Oorschot	0518859 W	1940	2000	0.0
Elandshoek	0517816 W	1940	2000	3.3
Rietvallei	0555441 W	1940	2001	5.0
Machadodorp	0517430 W	1940	2012	11.1
Kaapsehoop	0518455 W	1940	2000	28.3
Vlakplaats	0518186 W	1940	2001	4.9
Dullstroom	0554175 W	1940	2000	0.0
Mayfern	0556088 W	1940	2012	9.7
Weltevreden	0517762 W	1940	2012	4.2
Nelshoogte	0518589 W	1940	2012	4.2
Brooklands	0555405 W	1940	2012	1.4
Riverside	0557115 W	1940	2000	3.3
Witklip	0555673 W	1940	2012	0.0
Malelane	0556898 W	1940	2000	0.0
Krokodilbrug	0557712 W	1940	2012	0.0
Uitsoek	0555137 W	1940	2012	16.7
Discharge stations				
Boschrand	X2H005	1960	2012	0.0
Sassenheim	X2H008	1948	2012	2.8
Bellevue	X2H010	1948	2012	0.0
Geluk	X2H012	1956	2012	0.0
Lindenau	X2H015	1959	2012	4.9
Ten Bosch	X2H016	1960	2012	3.5
Dolton	X2H022	1960	2012	7.5
Bornmans Drift	X2H031	1966	2012	5.9
Weltevrede	X2H032	1968	2012	3.1
Witklip Dam	X2H068	1969	2012	0.0
Kwena Dam	X2H070	1979	2012	0.0

HESSD
11, 2719–2757, 2014

Table 2. SPI or SRI classes.

SPI or SRI range	Classification
SPI or SRI ≤ -2.0	Extremely dry
$-2.0 <$ SPI or SRI ≤ -1.5	Severely dry
$-1.5 <$ SPI or SRI ≤ -1.0	Moderately dry
$-1.0 <$ SPI or SRI ≤ 1.0	Near normal
$1.0 <$ SPI or SRI ≤ 1.5	Moderately wet
$1.5 <$ SPI or SRI ≤ 2.0	Severely wet
SPI or SRI ≥ 2.0	Extremely wet

Source: Sienz and Jahnke-Bornemann (2012)

HESSD
11, 2719–2757, 2014

Groundwater as an emergency source for drought mitigation, South Africa

F. E. F. Mussá et al.

Table 3. Water transfer in the Crocodile catchment.

Transfer from	Transfer to	Amount transfer ($Mm^3 yr^{-1}$)
Nelspruit	White River	3.0
* Sabie and Lomati	Kaap	8.5
Middle Crocodile	Lower Crocodile	25.6
* Sabie and Lomati	Lower Crocodile	6.0

Source: DWAF (2009), * Outside the Crocodile

HESSD
11, 2719–2757, 2014

Table 4. Abstractions simulation scenarios.

Scenarios	Recharge	Wells abstraction
Simulation 1	Reduced in 10 %	Increased in 10 %
Simulation 2	Reduced in 25 %	Increased in 25 %
Simulation 3	Reduced in 50 %	Increased in 50 %
Simulation 4	Reduced in 50 %	Increased in 100 %

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

11, 2719–2757, 2014

Groundwater as an emergency source for drought mitigation, South Africa

F. E. F. Mussá et al.

Table 5. Irrigation water requirements and water deficit per sub-catchment for the 1992–1995 drought.

Sub-catchment	Irrigation requirements ($Mm^3 yr^{-1}$)	Water deficit before applying existing drought mitigation plan ($Mm^3 yr^{-1}$)	GW abstraction needs after applying existing drought mitigation plan ($Mm^3 yr^{-1}$)
Kwena	6.43	0	0
Elands	12.47	0	0
Nelspruit	22.83	−8.1	11.0
White River	17.58	−35.5	27.0
Kaap	80.3	−12.8	24.0
Middle Crocodile	55.18	−15.4	10.4
Lower Crocodile	196.48	−88	24.6
Whole catchment	391.27	−159.8	97.0

HESSD
11, 2719–2757, 2014

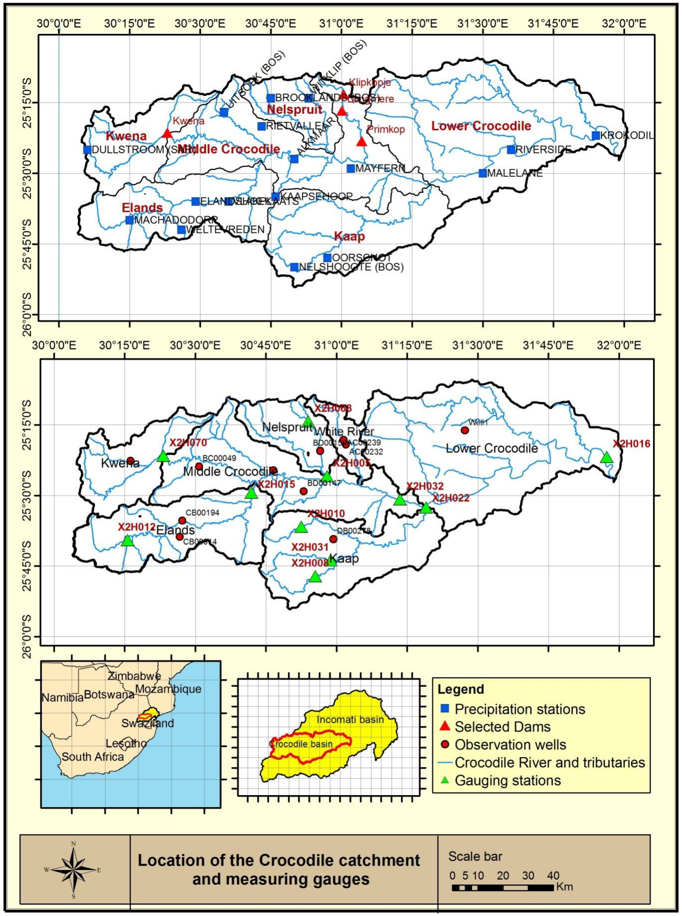

Fig. 1. Location of precipitation gauges, discharge stations, observation boreholes and catchment division in sub-catchments.

HESSD
11, 2719–2757, 2014

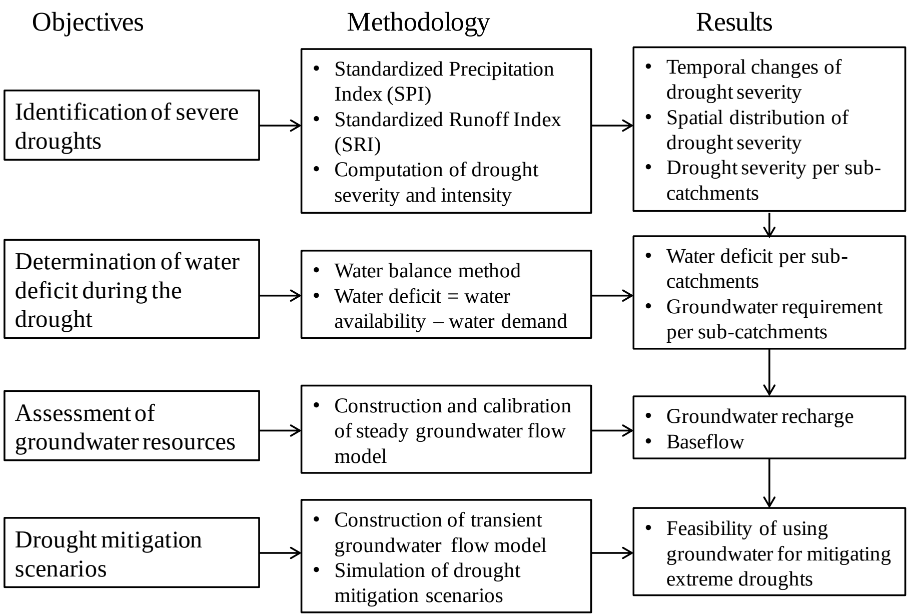

Fig. 2. Research methodology.

HESSD
11, 2719–2757, 2014

Groundwater as an emergency source for drought mitigation, South Africa

F. E. F. Mussá et al.

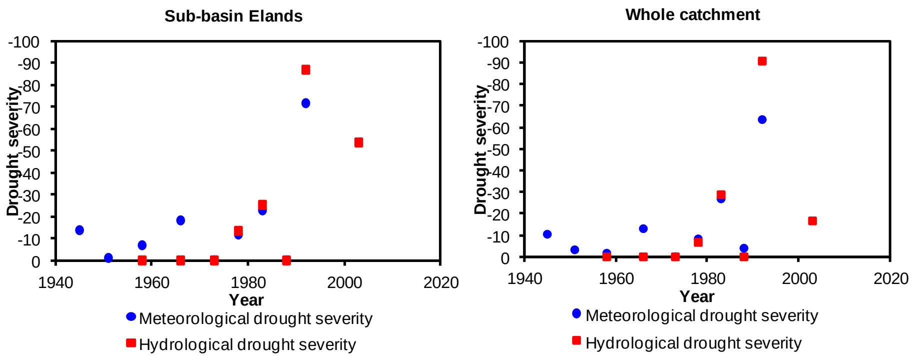

Fig. 3. Drought severity over time, sub-catchment Elands and the whole catchment.

HESSD
11, 2719–2757, 2014

Groundwater as an emergency source for drought mitigation, South Africa

F. E. F. Mussá et al.

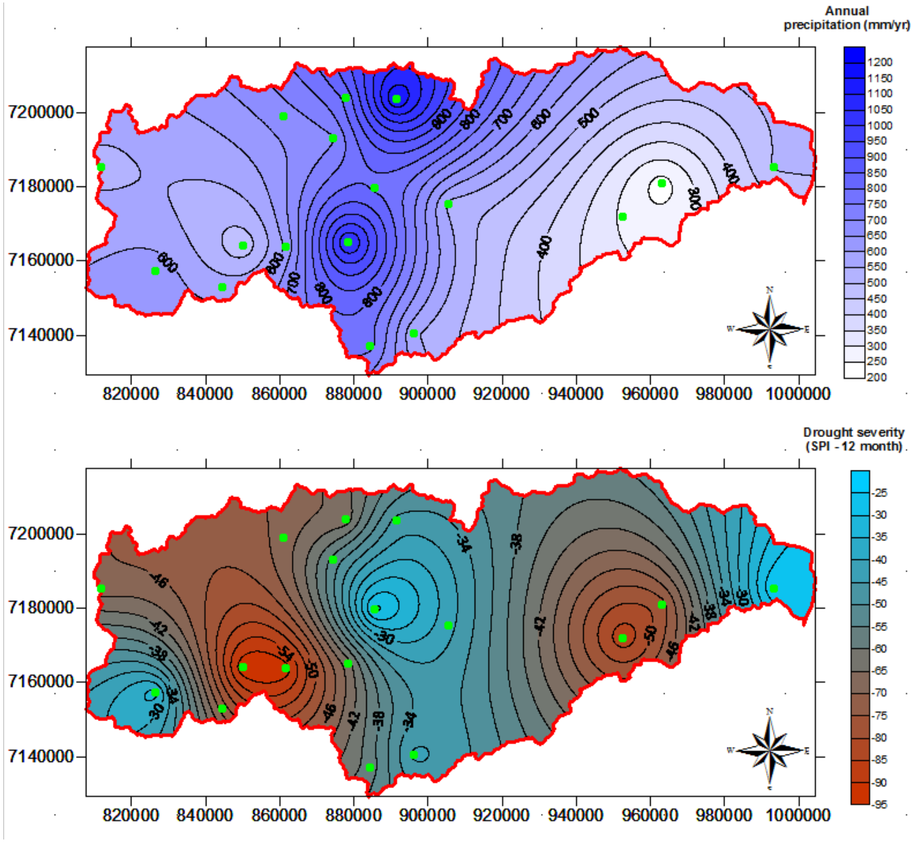

Fig. 4. Distribution of average annual precipitation and the meteorological drought severity during the 1992–1995 drought.

HESSD
11, 2719–2757, 2014

Groundwater as an emergency source for drought mitigation, South Africa

F. E. F. Mussá et al.

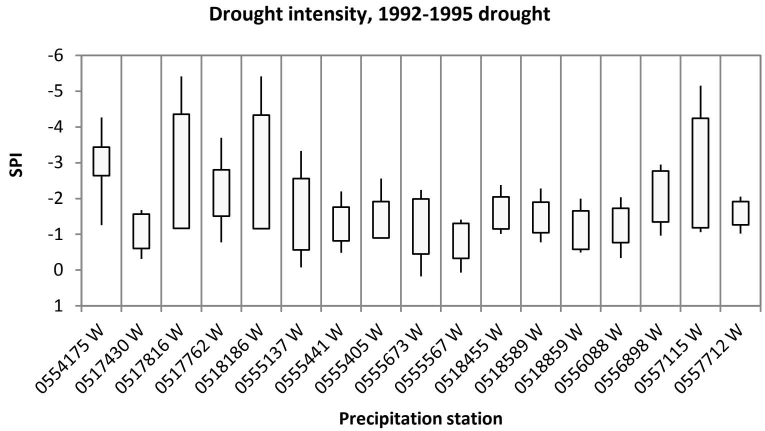

Fig. 5. Meteorological drought intensity during the 1992–1995 drought.

HESSD
11, 2719–2757, 2014

Groundwater as an emergency source for drought mitigation, South Africa

F. E. F. Mussá et al.

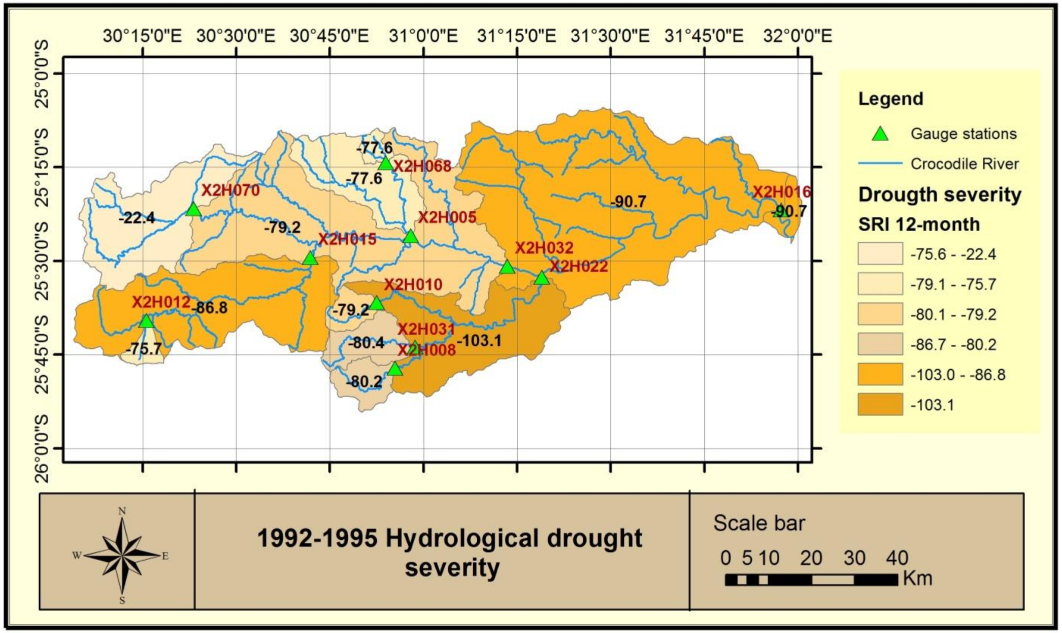

Fig. 6. Spatial variability of the hydrological drought severity during the 1992–1995 drought.

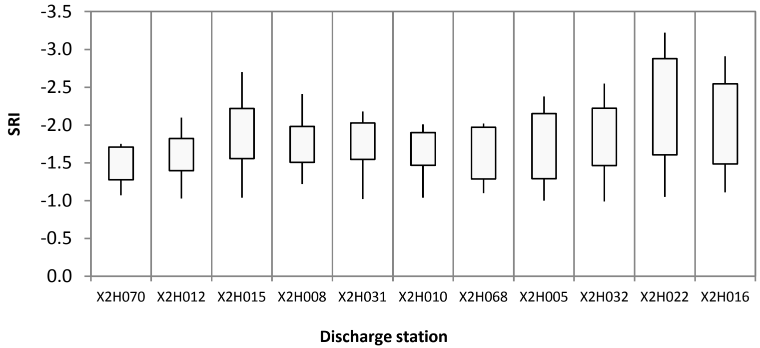

Fig. 7. Hydrological drought intensity during the 1992–1995 drought.

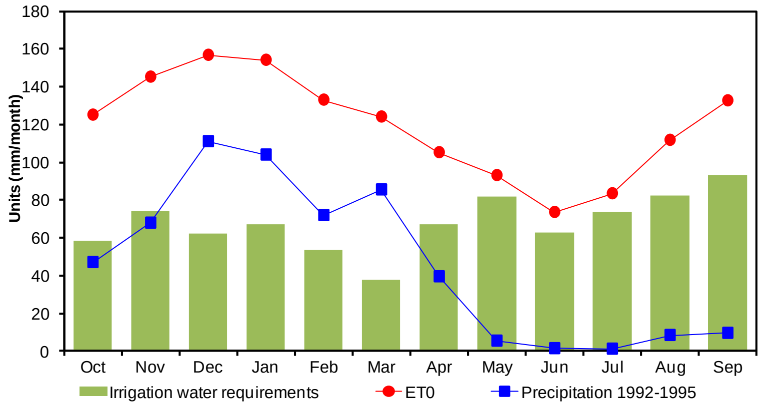

Fig. 8. Irrigation water requirements during drought period 1992–1995 for the whole catchment.

HESSD
11, 2719–2757, 2014

Groundwater as an emergency source for drought mitigation, South Africa

F. E. F. Mussá et al.

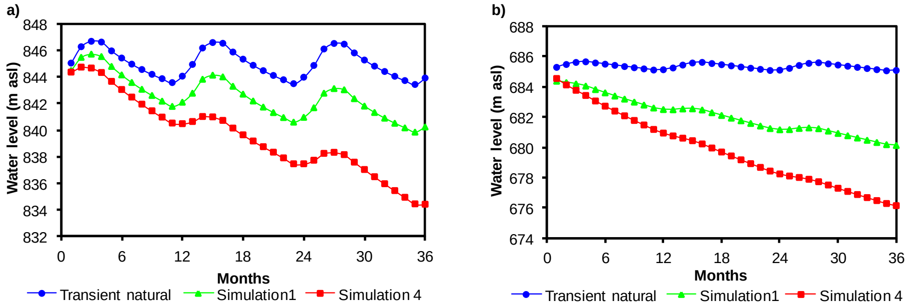

Fig. 9. Decrease of groundwater levels in **(a)** well observation AC00232 at White river catchment and **(b)** well observation BD00159 at Kaap river catchment.

HESSD

11, 2719–2757, 2014

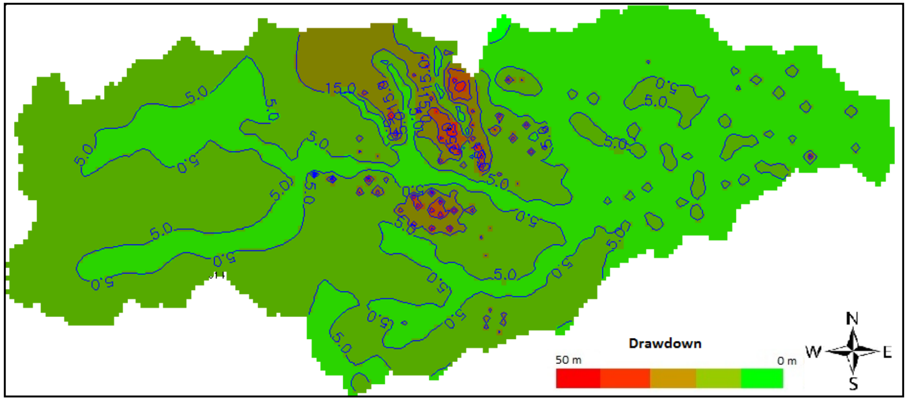

Fig. 10. Drawdown of groundwater levels after 3 years for Simulation scenario 4.

HESSD
11, 2719–2757, 2014

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

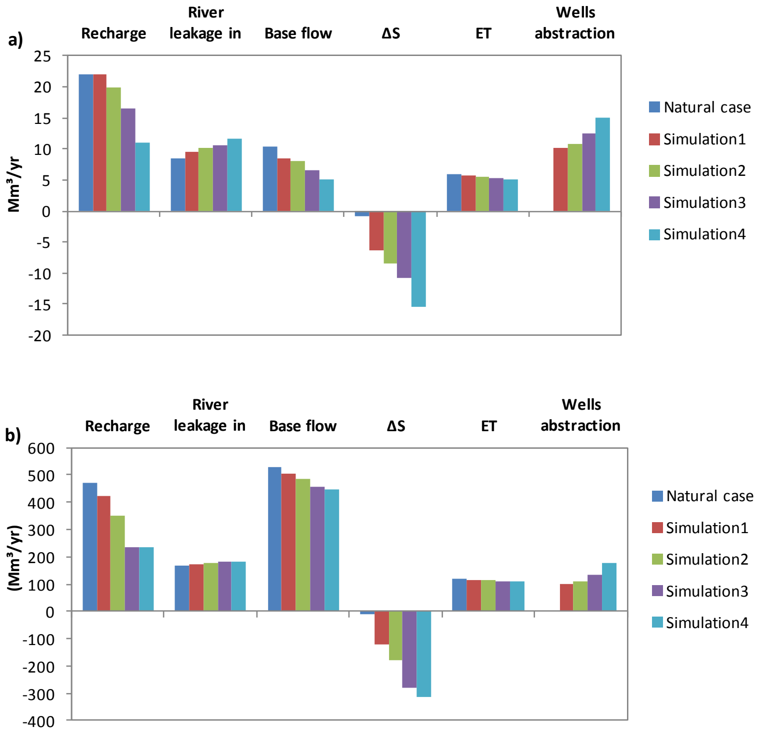

Fig. 11. Water balance components of 4 simulation scenarios for **(a)** White River and **(b)** whole catchment.

HESSD
11, 2719–2757, 2014

Groundwater as an emergency source for drought mitigation, South Africa

F. E. F. Mussá et al.