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Hydrological impact of rainwater harvesting in the Modder river basin of central South Africa

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Abstract

Along the path of water flowing in a river basin are many water-related human interventions that modify the natural systems. Rainwater harvesting is one such intervention that involves harnessing of water in the upstream catchment. Increased water usage at upstream level is an issue of concern for downstream water availability to sustain ecosystem services. The upstream Modder River basin, located in a semi arid region in the central South Africa, is experiencing intermittent meteorological droughts causing water shortages for agriculture, livestock and domestic purpose. To address this problem a technique was developed for small scale farmers with the objective of harnessing rainwater for crop production. However, the hydrological impact of a wider adoption of this technique by farmers has not been well quantified. In this regard, the SWAT hydrological model was used to simulate the hydrological impact of such practices. The scenarios studied were: (1) Baseline scenario, based on the actual land use of 2000, which is dominated by pasture (combination of natural and some improved grass lands) (PAST); (2) Partial conversion of Land use 2000 (PAST) to conventional agriculture (Agri-CON); and (3) Partial conversion of Land use 2000 (PAST) to in-field rainwater harvesting which was aimed at improving the precipitation use efficiency (Agri-IRWH).

SWAT was calibrated using observed daily mean stream flow data of a sub-catchment (419 km^2) in the study area. SWAT performed well in simulating the stream flow giving Nash and Sutcliffe (1970) efficiency index of 0.57 for the monthly stream flow calibration. The simulated water balance results showed that the highest peak mean monthly direct flow was obtained on Agri-CON land use (18 mm), followed by PAST (12 mm) and Agri-IRWH land use (9 mm). These were 19 %, 13 % and 11 % of the mean annual rainfall, respectively. The Agri-IRWH scenario reduced direct flow by 38 % compared to Agri-CON. On the other hand it was found that the Agri-IRWH contributed to more groundwater flow (40 mm) compared to PAST (32 mm) and Agri-CON (19 mm) scenarios. These results are in line with the intended purpose of Agri-IRWH.

Although there was a visible impact of the rainwater harvesting technique on the water yield when considered on a monthly time frame, the overall result suggests that the water yield of one of the upper Modder River Basin quaternary catchment may not be adversely affected by the Agri-IRWH land use scenario despite its surface runoff abstraction design.

1 Introduction

Along the path of water flowing in a river basin are many water-related human interventions, such as water storage, diversion, regulation, distribution, application, pollution, purification and other associated acts that modify the natural water systems. The common effect of all of these is that they impact on those who live downstream (Sunaryo, 2001), hence the need for a holistic approach of a river basin scale analysis and management. This approach would enhance the common understanding of the impacts of the different activities on the overall productivity of water and sustainability of natural resource use.

Rainwater harvesting which involves harnessing of water in the upstream catchment and is designed for "on-site" gains may have hydrological impacts on downstream water availability (Ngigi, 2003). Increased water consumption at upstream level is an issue of concern for downstream water availability, but it is generally assumed that there are overall gains and synergies by maximizing the efficient use of rainwater at farm level (Rockstrom, 2001). However, expansion of rainwater harvesting practices could have unintended hydrological consequences on river basin water resources and may have negative implications on downstream water availability to sustain hydro-ecological and ecosystem services.

The expected upstream shifts in water flows may result in complex and unexpected downstream effects in terms of quantity and quality of water. In general, though, increasing the residence time of runoff flow in a catchment through rainwater harvesting may have positive environmental as well as hydrological implications/impacts downstream (Rockstrom et al., 2002). However, it may also result in uninformed decisions by policy makers. For instance, Irrigation Department in India ordered the destruction of community rainwater harvesting structures, fearing that it would threaten the supply of irrigation water to downstream users (Agarwal et al., 2001). Therefore, there is a need for further research and understanding on the possible impact of wider expansion of rainwater harvesting technologies for agriculture in a river basin.

The Modder River basin, located in the semi-arid regions of central South Africa, is experiencing intermittent meteorological droughts causing water shortages for agriculture, livestock and domestic purposes. The irrigated agriculture in the basin draws water mainly by pumping out of river, pools and weirs. However, many of the rural developing farmers rely on rain-fed agriculture for crop production. In the past few years the Institute for Soil, Climate and Water (ISCW) of the Agricultural Research Council (ARC) has introduced a micro-basin tillage technique which can be used as an in-situ rainwater harvesting, known as infield rain water harvesting (IRWH), for small scale farmers in the basin with the objective of harnessing rain water for crop production (Hensley et al., 2000). They found that with the use of the IRWH technique (Fig. 1) the surface run-off was reduced to minimum and evaporation from the basin soil surface was reduced considerably when mulching is used in the basin. The technique also enhances runoff stored in the basin to infiltrate and to be stored in the sub-soil; ultimately resulting in a significant increase in crop yield (30–50 %) compared to conventional tillage practices (Botha et al., 2003).

Based on the specific biophysical and socioeconomic requirement of IRWH, some studies were carried out to estimate the suiTables areas for IRWH. For instance, Woyessa et al. (2006) estimated 27 % of the upper Modder river basin area as suiTables for IRWH based on biophysical conditions. However, Mwenge Kahinda et al. (2008a and b) estimated 79 % of the basin as suiTables for IRWH considering both biophysical and socioeconomics criteria in their assessment. In one of the quaternary catchments of the upper Modder river basin (C52A), however, Mwenge Kahinda et al. (2009) found only 14 % of the basin area as suiTables for IRWH. Mwenge Kahinda et al. (2009) also conducted a study on the hydrological impact of IRWH by considering the monthly median flow (wettest season flow) of C52A catchment when 100 % of the estimated suitables areas are under IRWH. They reported that the 100 % adoption scenario significantly reduced the high flow compared to the actual land use of 2000 or 0 % adoption. They also showed that "the most likely scenario", which is about 10 % of the area being adopted for IRWH, gave no significant difference compared to the 0 % adoption. However, non of the above studies demonstrate the impact of the different land use scenarios on the stream flow components and water balance of the catchment.

Numerous modelling approaches have been developed to simulate the impact and consequences of land use changes on the environment in general and water resources in particular. One of these models is the Soil and Water Assessment Tool (SWAT), which was developed by the USDA to simulate the impacts of land-use changes and land management practices on water balance of catchments (Arnold et al., 1998). Many research reports have demonstrated the robustness of the model in simulating satisfactorily most of the water balance components of catchments (Gassman et al., 2007). SWAT has also proven to be an effective tool for understanding pollutions from fertilizer applications and point sources (Arnold et al., 1998; Fohrer et al., 2005) and for wider environmental studies (Gassman et al., 2007). The model is also used as a decision support tool in land use planning by simulating the impact of different land use scenarios on water resources (Fohrer et al., 2001; Chanasyk et al., 2003; Conan et al., 2003b; Mapfumo et al., 2004; Wei et al., 2008; Cao et al., 2009).

Taking into account its wider application in assessing the impact of land use changes on water resources, SWAT model (version 2005) was applied in the Modder river basin of Central South Africa to evaluate the impact of land use change on water resources, with particular emphasis on the flow of water into Rustfontein dam. The main aim of this study was to assess the hydrological impact of in-situ rainwater harvesting in the Upper Modder River Basin of Central South Africa.

This research hypothesizes that expansion of infield rain water harvesting in the upstream of the catchment will have impacts on the different components of catchment stream flow.

2 Materials and methods

2.1 Study site

The Modder River basin is a large basin with a total area of 17, 380 km^2. It is divided into three sub-basins, namely the Upper Modder, the Middle Modder and the Lower Modder. The study was carried out in the Upper Modder River Basin specifically in the quaternary catchment, C52A (Fig. 2), which is located between 26.48° and 26.87° East and 29.25° and 29.62° South. The C52A quaternary catchment receives mean annual rainfall of 537 mm and has an area of 927.6 km^2. The study area was delineated by ArcSWAT based on the geographic coordinates of the flow gauging station at the outlet of the catchment and a digital elevation model (DEM with a resolution of 90 m by 90 m) of C52. The DEM was obtained from the Institute for Soil, Climate and Water (ISCW). The soil of the catchment is dominated by sandy clay loam and sandy clay textured soil types.

2.2 Data analysis procedures

Sensitivity and calibration analyses for parameters used in the model were carried out using SWAT statistical module. Calibration was carried out on the most sensitive input parameters of the model using auto-calibration module of SWAT using the observed flow data recorded at the gauge C5H056 in C52A catchment during the year 2002. This was conducted in order to optimize the values of those parameters ranked 1 to 7 during sensitivity analysis.

As indicated in Fig. 4, there are two gauging stations in the catchment. The gauging station C5R003 measures discharge from the whole of C52A catchment

(927 km^2) while the second gauging station C5H056 measures the discharge from a sub-catchment with a contributing area of 412 km^2.

Following model calibration, an assessment of land use change impact on the water balances of catchment C52A was undertaken by using present land use (land use 2000) and two land use scenarios. In this study, land use data of the year 2000 was used as a bench mark against which two land use scenarios were compared. Daily weather data from 1993 to 2007 was used for the simulations. The data for the first two years were used to warm up the SWAT model. Once the model was set up and calibrated, the water balance of C52A was simulated by changing the land use scenarios only. Simulations were conducted on daily as well as monthly time steps, but the results were interpreted using mean monthly values.

The two land use scenarios considered were: (1) conventional land use which represents the current land use practice in the area, and (2) in-field rainwater harvesting, based on the work of Hensley et al. (2000), which was aimed at improving the precipitation use efficiency by reducing surface runoff. The 2000 land use data of C52A shows that 84 % of the land is covered by pasture (PAST). This was taken as a base scenario against which the other two scenarios were compared (Fig. 3b and Tables 1). To create the first scenario (Agri-CON), a change was made to the original pasture (PAST) land in such a way that the pasture covered area on slopes of 0 to 3 % was converted to agricultural land (cropped with maize) with conventional tillage practices (Fig. 3d and Table 2). The slope ranges were selected in such a way that it satisfies the FAO slope classification standard (FAO, 1990) and the suitables slope range for IRWH (Mwenge Kahinda et al., 2008a). This change brought about a conversion of 420 km^2 (54 %) of the pasture area on slopes of 0 to 3 % to agricultural land thus increasing the area of the agricultural land from 8 % to 53 % and decreasing the pasture area from 84 % to 39 %. The second scenario (Agri-IRWH) was obtained by changing the pasture land (PAST) located on slopes of 0 to 3 % to an agricultural land planted with maize using an infield rainwater harvesting (IRWH) (Fig. 3d and Table 1). In both scenarios all other land use types remained the same as in the base-case scenario and they both have the same area of cropland and crop type which is maize, the only difference being tillage type, i.e. scenario-1 uses conventional row cropping while scenario-2 uses IRWH. In both scenarios, socio-economic factors were not considered as part of a requirement to the land use changes made.

The curve number for antecedent soil moisture condition two (CN2) and tillage management were modified for Agri-IRWH in order to satisfy the surface condition created by IRWH. The change of land use from pasture to maize conventional planting and IRWH was done using ARCSWAT.

3 Results and discussions

3.1 Sensitivity analysis

During simulation procedures, default and measured parameters which were used for simulation of the water balance underwent a sensitivity analysis test. The sensitivity analysis was conducted using the observed flow data of the gauging station C5H056 (Fig. 4). For the gauging station, the observed data of daily average flows were available for nine years (1999 to 2007).

Stream flow simulations were conducted using SWAT model and the parameters were analysed for their sensitivity on the total stream flow discharge using SWAT's sensitivity analysis module. These are ranked and presented in Tables 3.

3.2 Calibration

Results of the calibration analysis revealed an R^2 (coefficient of determination) of 0.68 and a D-index (agreement index) of 0.86 (Table 4). The systematic and unsystematic root mean square errors (RMSEs and RMSEu) are also minimal. The ratio of the unsystematic root mean square error (RMSEu) to the root mean square error provided a value of 0.87, indicating good correlation between the observed and simulated objective functions and that the error is not possibly of a systematic nature (Welderufael et al., 2009). The Nash and Sutcliffe (NS) index/efficiency (1970) revealed a value of 0.57 for the monthly stream flow calibration, describing a satisfactory correlation between the observed and simulated monthly stream discharges. Figure 5 shows the plot of observed and simulated streamflow data.

Although the statistical performance was found to be satisfactory, simulation of the daily stream flow or the water yield of the sub-basin using the calibrated parameters provided a result that failed to capture some of the peak flows (Fig. 5). According to Winchell et al. (2007), this happens when precipitation data was obtained from non-representative meteorological station or if there is a malfunctioning of flow gauge. In our study, the latter appears to be the most likely cause. The rainfall data which was obtained from South Africa Weather Service for three stations within the C52A catchment appear to be reliable (Fig. 4).

3.3 Water balance of the catchment (C52A)

The impacts of the different land use scenarios on the water balance of the catchment are presented in Fig. 5 and Tables 5 and 6. The simulated mean monthly water yield (WY = DIRQ + GWQ-transmission loss) during the period of 1995 to 2007 showed significant reductions in peak flow when PAST land on 0 to 3 % slope was converted to Agri-CON and Agri-IRWH land use types. The simulated monthly mean peak WYs were 20 mm, 18 mm and 16 mm for Agri-CON, Agri-IRWH and PAST, respectively. The mean monthly WY under the Agri-CON land use scenario was higher than the other two scenarios during the rainy months of December to March only (Fig. 6b). During the remaining months, the two land use types (Agri-IRWH and PAST) recharged the groundwater better and had higher WYs than the Agri-CON land use scenario. Agri-IRWH showed a higher peak WY value (12.5 %) than PAST probably due to the high groundwater flow contribution by the IRWH technique during the same month as the occurrence of the peak flow. The F-test for two sample variances of the mean monthly WYs revealed no significant differences among the three land use scenarios (Table 6).

The effect of the different land use scenarios on the water balance of C52A is well demonstrated by the direct flow (DIRQ) component of the WY. Figure 7a presents the direct flow component of the three land use scenarios. The highest mean monthly peak flow of DIRQ was obtained under Agri-CON land use, amounting to about 18 mm followed by PAST with 12 mm. Agri-IRWH land use scenario generated the lowest DIRQ which amounted to 9 mm. Similarly, the mean annual DIRQs were 71, 52, and 45 mm under AgriCON, PAST, and Agri-IRWH land use scenarios, respectively. The F-test for the DIRQ gave a significant difference ($P < 0.02$) between Agri-IRWH and Agri-CON land scenarios while there was no significant difference between Agri-IRWH and PAST as well as between PAST and Agri-CON (Table 8). All the DIRQs generated under the Agri-IRWH scenario came from the lateral flow (LATQ) component of the direct flow (Table 5). The surface runoff (SURQ) component from IRWH portion of the Agri-IRWH scenario shows no literal runoff during the whole study period (1995–2007) (Table 5). Generally, the results of the simulation demonstrated that the annual WY was affected slightly by the different land use scenarios, which were 89 mm, 84 mm and 83 mm for Agri-CON, PAST and Agri-IRWH, respectively (Fig. 5). Mwenge Kahinda et al. (2008a) reported that there was no significant change in the overall WY by the introduction of IRWH in the quaternary catchment C52A.

As per its intended purpose, Agri-IRWH technique reduced the direct flow by 37 % and the surface runoff component by almost 100 % compared to the Agri-CON land use scenario. This obviously improves the soil water availability within the crop root zone as well as the precipitation use efficiency (PUE). Rain-fed agriculture using Agri-IRWH technique in this area has been reported to have increased production of maize and sunflower by about 50 % compared to Agri-CON production (Hensley et al., 2000; Botha et al., 2003, 2007). Woyessa et al. (2006) have also demonstrated that IRWH improved both crop production and monetary income of a farmer more than the conventional land preparation method that uses supplemental irrigation system by harvesting the direct runoff in small dams or ponds.

The other interesting result on the impact of land use change was related to the groundwater flow (base flow) component of the WY. Figure 6c presents the groundwater flow component of the stream flow. Agri-IRWH, due to its surface runoff harnessing design, collects the runoff generated from the two meter strip and stores it in the one meter wide basin. By doing so it allows more water to infiltrate into the soil and percolate a significant amount further deep into the groundwater table than the Agri-CON land use scenario (Table 6).

Thus, the Agri-IRWH was found to recharge the groundwater table significantly ($P <$ 0.03) than the Agri-CON scenario (Table 9). The build up of the water Tables under the AgriIRWH will in turn contribute to the recharge of the C52A stream as a base flow. Thus, the highest mean monthly peak groundwater flow was produced by Agri-IRWH amounting to 10 mm, followed by 7 mm and 4 mm by PAST and Agri-CON land use scenarios, respectively. Tables 10 also shows that there is highly significant difference ($P < 0.01$) between Agri-IRWH and Agri-CON in their monthly mean GWQ. In case of the annual groundwater flow, the results of the scenarios were in reverse sequence compared to the direct flow. The highest annual groundwater flow was obtained from AgriIRWH which was 37 mm, followed by 32 mm under PAST and 18 mm under Agri-CON land use scenarios. The base flow showed an increase of about 105 % under Agri-IRWH compared to AgriCON land use scenario. The F-test for the mean annual deep percolation (1995–2007) also revealed a significant difference ($P < 0.03$) between Agri-IRWH and Agri-CON. There was also a significant difference ($P < 0.04$) between PAST and Agri-CON in terms of annual deep percolation. However, there was no significant difference between Agri-IRWH and PAST (Table 9). The results demonstrate that there was higher infiltration of water under Agri-IRWH and PAST than under the Agri-CON land use scenario. The Agri-IRWH technique creates a pond of water inside the furrow that later infiltrates into the soil profile. Moreover, Agri-IRWH and PAST scenarios were found to increase the residence time of runoff flow in a catchment which in turn had an effect on the occurrence of the monthly WY peak flows. Thus, the increased dry season WY under Agri-IRWH may have positive environmental as well as hydrological implications/impacts downstream by providing more stream flow during the dry season.

With regard to the simulated evapotranspiration (ET), there was no significant difference in the total annual amount, but there was a marked difference between the monthly ET distribution of grass and maize crops (Fig. 6d). The ETs from Agri-CON and Agri-IRWH land uses followed the same pattern due to the fact that the same type of crop (maize) was considered in both cases. The annual ET under Agri-IRWH showed a 4 mm more water use than both Agri-CON and PAST land use scenarios.

4 Conclusions

The SWAT hydrological model was used to analyse two land use scenarios in comparison to the 2000 base line land use type. The model was able to illustrate the impact of different land use types on the water resources of quaternary catchment C52A. The results of the scenario analysis revealed that conventional agricultural land use type generated the highest direct flow compared to the ones dominated by pasture or IRWH land use types. The conventional agriculture may not support favourable crop production on rain-fed semi-arid areas, such as the Modder river basin, due to the decreased infiltration of water to the sub-soil which ultimately influences the soil water content within the root zone.

The results also confirmed that there was improvement of water infiltration into the soil by Agri-IRWH and PAST land use types. Both resulted in higher base flow than AgriCON land use type and demonstrated high deep water percolation with a significant difference in annual amounts compared to Agri-CON. The Agri-IRWH showed 105 % higher base flow compared to the AgriCON land use scenario.

Overall, the results suggest that the WY of C52A may not be adversely affected by the Agri-IRWH land use scenario despite its design for surface runoff abstraction. It is expected that this result will assist in taking a proactive measure regarding water resources management in general and a strategic allocation and use of water in particular.

However, still there remains some uncertainties in simulating the lateral and groundwater flow components of the water yield due to the limited data in soil physical properties such as soil texture, soil hydraulic conductivity, soil water holding capacity, etc., which have major influences on the water yield components. Anyhow, we believe that the calibration of the sensitive soil physical parameters could minimize the uncertainty.

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Table 1. Actual land use of C52A in 2000 and the two land use scenarios.

Land use type	Area and percentage		Area and percentage under Agri-CON or Agri-IRWH	
	Area (km^2)	(%)	Area (km^2)	(%)
Agriculture (AGRR)	72.4	7.8	492.4	53.1
Ever green forest (FRSE)	2.2	0.2	2.2	0.2
Pasture (PAST)	780.0	84.1	360.0	38.8
Range plus brush land (RNGB)	42.0	4.5	42.0	4.5
Urban (URBN)	6.1	0.7	6.1	0.7
Water bodies (WATR)	10.5	1.1	10.5	1.1
Wet land (WETN)	14.0	1.5	14.0	1.5
Total	927.2	100.0	927.1	100.0

Table 2. C52A slope ranges and area coverage.

Slope range (%)	Area (km^2)	(%)
0–3	524.1	56.5
3–8	319.0	34.4
> 8	84.0	9.1
Total	927.1	100.0

Table 3. Results of sensitivity analysis using SWAT Model.

Parameter	Rank
Curve number for land use	1
Soil available water capacity	2
Threshold depth of water in the shallow aquifer required for return flow to occur	3
soil evaporation compensation factor	4
Soil layer depth	5
Ground water "revap"* coefficient	6
Soil saturated hydraulic conductivity	7
Average slope length of sub basin	8
Threshold depth of water in the shallow aquifer for "revap" to occur	9
Surface lag time	10
Effective hydraulic conductivity in main channel alluvium	11
Moist soil albedo	12
Average slope of sub basin	13

* *Revap*: SWAT models the movement of water into overlaying unsaturated layers as a function of water demand for evapotranspiration. To avoid confusion with soil evapotranspiration this process has been termed "*revap*".

Table 4. Calibration performance statistics.

Indices	Value
Slope (b)	1.07
Intercept (a)	0.08
RMSE	0.18
RMSEs	0.09
RMSEu	0.16
MAE	0.12
R^2	0.68
D-index	0.86
RMSEu:RMSE	0.87
Nash and Sutcliffe (1970) efficiency, NS*	0.57

* = Value for monthly stream flow calibration.

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Table 5. Simulated annual deep water percolation under the different land use scenarios.

Year	Precipitation	Annual deep percolation in mm		
	(mm)	Agri-IRWH	PAST	Agri-CON
1995	590.7	0.6	3.3	0.6
1996	755.5	110.3	67.1	45.4
1997	452.8	20.3	22.2	11.6
1998	811.5	78.3	59.0	28.0
1999	433.0	0.0	0.0	0.0
2000	591.3	7.9	14.2	4.3
2001	934.3	122.2	135.3	70.5
2002	531.3	28.3	21.4	12.4
2003	425.6	4.0	11.6	3.1
2004	403.7	0.0	0.0	0.0
2005	541.9	1.3	2.9	1.3
2006	910.8	168.7	174.3	104.4
2007	396.1	0.2	0.2	0.2
Mean	598.4	41.7^{*}	39.3^{*}	21.7^{**}

Numbers followed by different number of asterisks are significantly different at $P < 0.05$.

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Table 6. Components of the direct flows under the three land-uses scenarios.

YEAR	PREC	PAST			Agri-CON			Agri-IRWH		
	(mm)	SURQ (mm)	LATQ (mm)	DIRQ (mm)	SURQ (mm)	LATQ (mm)	DIRQ (mm)	SURQ (mm)	LATQ (mm)	DIRQ (mm)
1995	590.7	10.61	18.23	28.84	16.47	30.25	46.72	0.00	31.07	31.07
1996	755.5	61.18	27.46	88.64	85.93	42.50	128.43	0.00	51.40	51.40
1997	452.8	8.13	16.02	24.15	12.17	25.57	37.74	0.00	26.62	26.62
1998	811.5	75.12	28.98	104.10	86.53	45.25	131.78	0.00	54.23	54.23
1999	433.0	1.49	12.84	14.33	3.31	22.32	25.63	0.00	22.44	22.44
2000	591.3	6.40	20.41	26.81	10.94	31.43	42.37	0.00	32.15	32.15
2001	934.3	118.85	38.03	156.88	98.32	54.86	153.18	3.88	66.89	70.77
2002	531.3	14.43	18.67	33.10	26.47	29.91	56.38	0.00	32.24	32.24
2003	425.6	19.19	13.53	32.72	23.42	22.33	45.75	0.00	24.14	24.14
2004	403.7	0.08	11.98	12.06	0.72	19.65	20.37	0.00	19.67	19.67
2005	541.9	0.78	16.32	17.10	1.72	25.17	26.89	0.00	25.24	25.24
2006	910.8	104.82	42.44	147.26	112.30	58.19	170.49	0.00	70.42	70.42
2007	396.1	4.11	11.45	15.56	6.98	18.49	25.47	0.00	18.83	18.83
Sum	7778.66	425.19	276.36	701.55	485.28	425.92	911.20	3.88	475.34	479.22

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Table 7. F-test two-sample for variances for the mean monthly WY.

Statistics	IRWH Vs CON		IRWH Vs PAST		CON Vs PAST	
	IRWH	CON	IRWH	PAST	CON	PAST
Mean	6.8967	7.4092	6.8967	7.0350	7.4092	7.0350
Variance	28.6386	41.2499	28.6386	28.2361	41.2499	28.2361
Observations	12	12	12	12	12	12
df	11	11	11	11	11	11
F	0.6943		1.0142		1.4609	
P(F < = f) one-tail	0.2776		0.4908		0.2700	
F Critical one-tail	0.3549		2.8179		2.8179	

Table 8. F-Test Two-Sample for Variances for the mean monthly DIRQ.

Statistics	IRWH Vs CON		IRWH Vs PAST		CON Vs PAST	
	IRWH	CON	IRWH	PAST	CON	PAST
Mean	3.7683	5.9033	3.7683	4.3775	5.9033	4.3775
Variance	9.6360	33.8312	9.6360	17.8911	33.8313	17.8911
Observations	12	12	12	12	12	12
df	11	11	11	11	11	11
F	0.2848		0.5386		1.8909	
P(F < = f) one-tail	0.0241		0.1597		0.1528	
F Critical one-tail	0.3549		0.3549		2.8179	

Table 9. F-Test Two-Sample for Variances for annual deep percolation (1995–2007).

Statistics	IRWH Vs CON		IRWH Vs PAS		PAST Vs CON	
	IRWH	CON	IRWH	PAST	PAST	CON
Mean	41.7000	21.6769	41.7	39.3461	21.6769	39.3461
Variance	3364.7850	1077.0602	3364.78	3154.2310	1077.0602	3154.2310
Observations	13	13	13	13	13	13
df	12	12	12	12	12	12
F	3.1240		1.0667		0.3415	
P(F < = f) one-tail	0.0297		0.4563		0.0373	
F Critical one-tail	2.6866		2.6866		0.3722	

Table 10. F-Test Two-Sample for Variances for the mean monthly GWQ.

Statistics	IRWH Vs PAST		IRWH Vs CON		CON Vs PAST	
	IRWH	PAST	IRWH	CON	CON	PAST
Mean	3.1283	2.6575	3.1283	1.5058	1.5058	2.6575
Variance	11.9254	4.8566	11.9254	2.4207	2.4207	4.8566
Observations	12	12	12	12	12	12
df	11	11	11	11	11	11
F	2.4555		4.9265		0.4984	
$P(F <= f)$ one-tail	0.0759		0.0068		0.1318	
F Critical one-tail	2.8179		2.8179		0.3549	

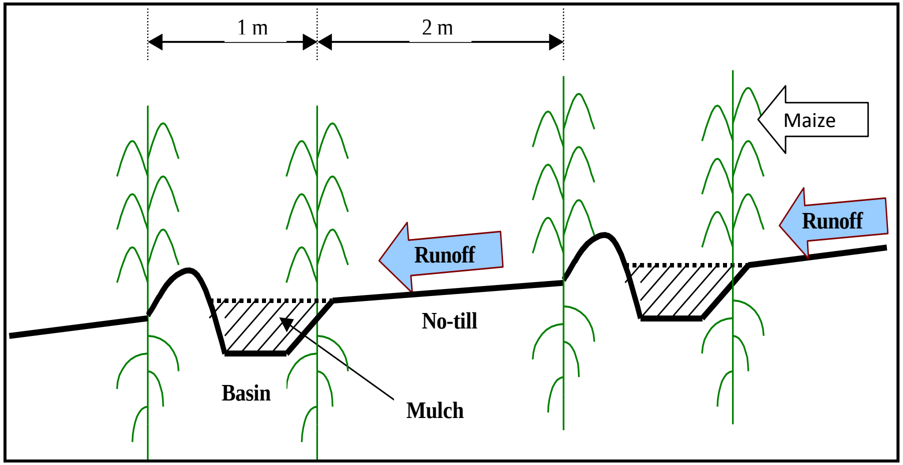

Fig. 1. Diagrammatic representation of the IRWH technique (Adapted from Hensley et al., 2000).

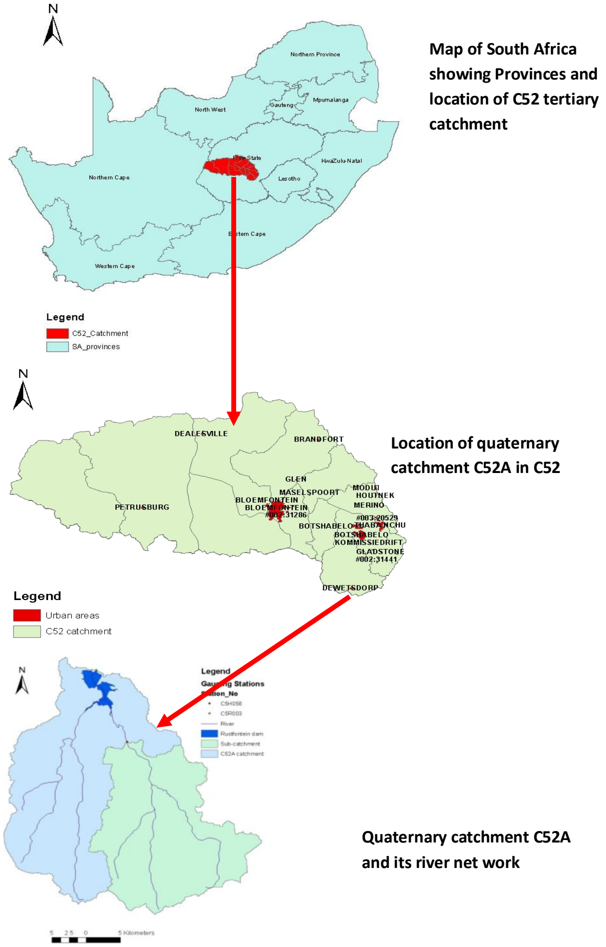

Fig. 2. Location of the Modder river basin and the study area (C52A).

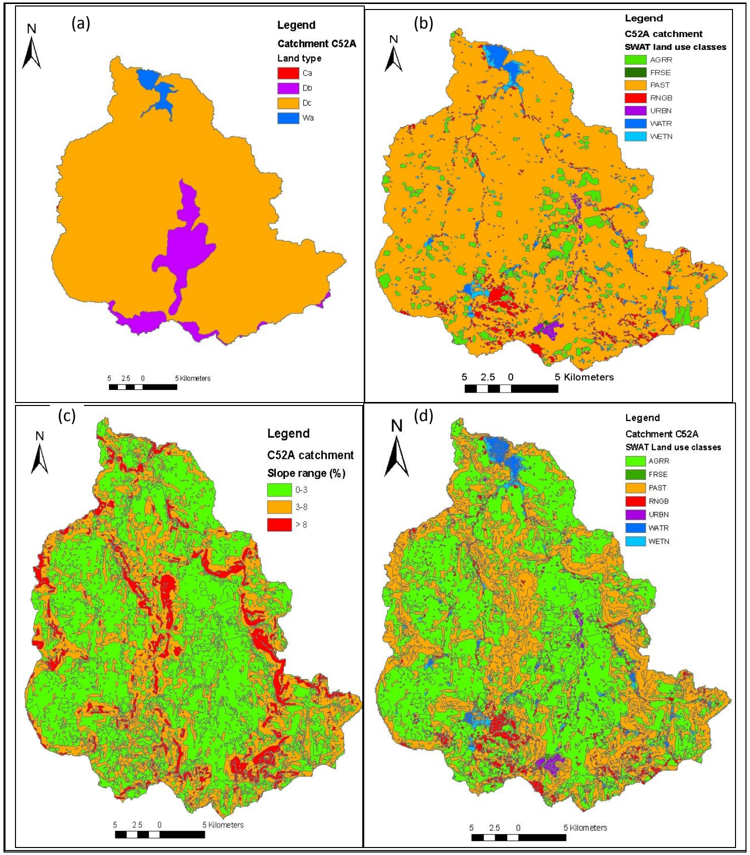

Fig. 3. Land use and topography of the study site: **(a)** Land type; **(b)** Land use 2000; **(c)** Slope range; and **(d)** agriculture on slopes of 0–3 %.

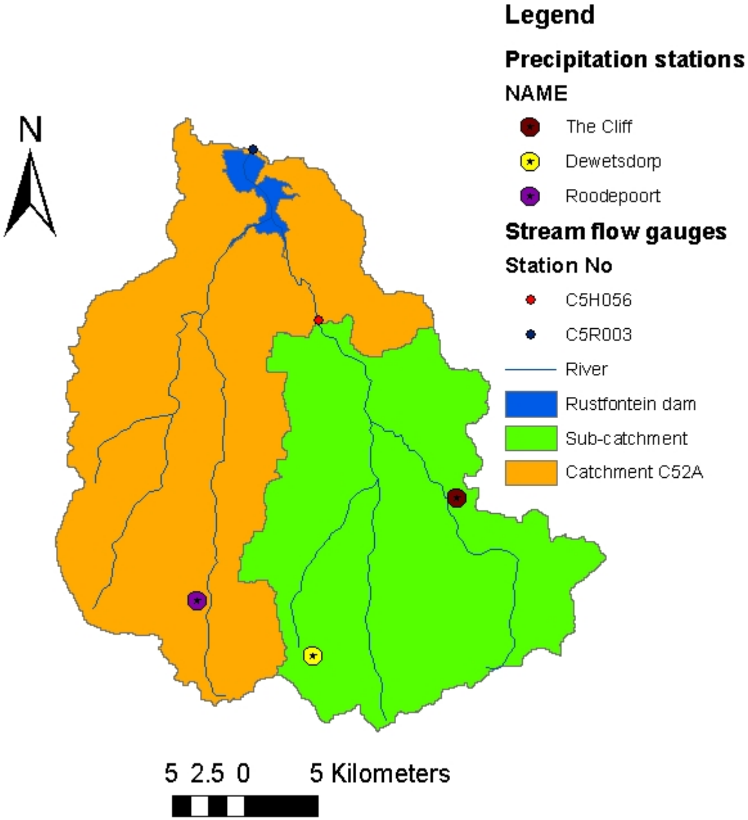

Fig. 4. Sub-catchments of C52A and locations of rain and stream flow gauging stations.

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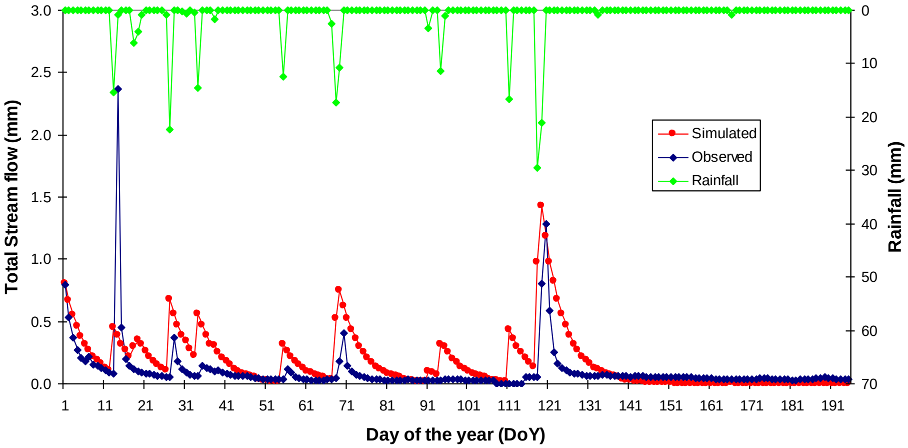

Fig. 5. Observed and simulated daily stream flow (Q) after calibration at gauging station C5H056.

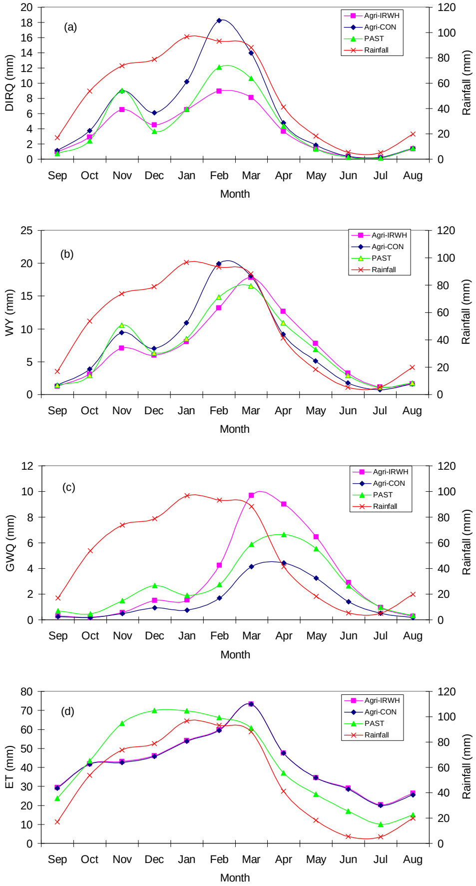

Fig. 6. Water balance components: **(a)** Direct flow; **(b)** Base flow; **(c)** Total water yield; and **(d)** Evapotranspiration in the quaternary catchment (C52A) under three land use scenarios.