Agricultural Water Management 116 (2013) 218–227

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Impact of rainwater harvesting on water resources of the modder river basin, central region of South Africa

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ARTICLE INFO

Article history:
Received 2 May 2012
Accepted 27 July 2012
Available online 18 August 2012

Keywords:
Hydrology
Catchment
Land use
Water harvesting

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 collecting and use of surface runoff for different purpose in the upstream catchment. Increased water consumption at upstream level is an issue of concern for downstream water availability to sustain ecosystem services. The upper Modder River basin, located in a semi arid region in the central South Africa, is experiencing intermittent droughts causing water shortages for agriculture, livestock and domestic uses. To address this problem a technique was developed for small scale farmers with the objective of collecting and concentrating of 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 potential 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 actual land use 2000 (PAST) to conventional agriculture (Agri-CON); and (3) partial conversion of actual land use 2000 (PAST) to in-field rainwater harvesting which was aimed at improving the precipitation use efficiency (Agri-IRWH).

SWAT was calibrated using both observed daily as well as monthly streamflow data of a sub-catchment (419 km^2) in the study area. SWAT performed well in simulating the streamflow giving Nash and Sutcliffe efficiency of 0.57 for the monthly streamflow calibration. The simulated water balance results showed that the highest peak mean monthly direct flow was obtained under the 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 the annual direct flow by 32% compared to Agri-CON which is significant at $p < 0.02$ level. On the other hand it was found that the Agri-IRWH contributed to more groundwater recharge (40 mm/year) compared to PAST (32 mm/year) and Agri-CON (19 mm/year) scenarios. Although there was observable impact of the rainwater harvesting technique on the water yield when considered on a monthly time frame, the overall result suggests that the annual water yield of one of the upper Modder River Basin quaternary catchment will not be adversely affected by the Agri-IRWH land use scenario despite its surface runoff capture design.

1. Introduction

In a river basin, there 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; Ngigi et al., 2006, 2008), hence the need for a holistic approach of a river basin scale analysis and management. This approach should 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 collection of surface runoff in the upstream catchment and is designed for upstream water consumption, may have hydrological impacts on downstream catchment water availability (Ngigi, 2003; Ngigi et al., 2008; Makurira et al., 2009). 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 et al., 2002; Ngigi et al., 2008). 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

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http://dx.doi.org/10.1016/j.agwat.2012.07.012

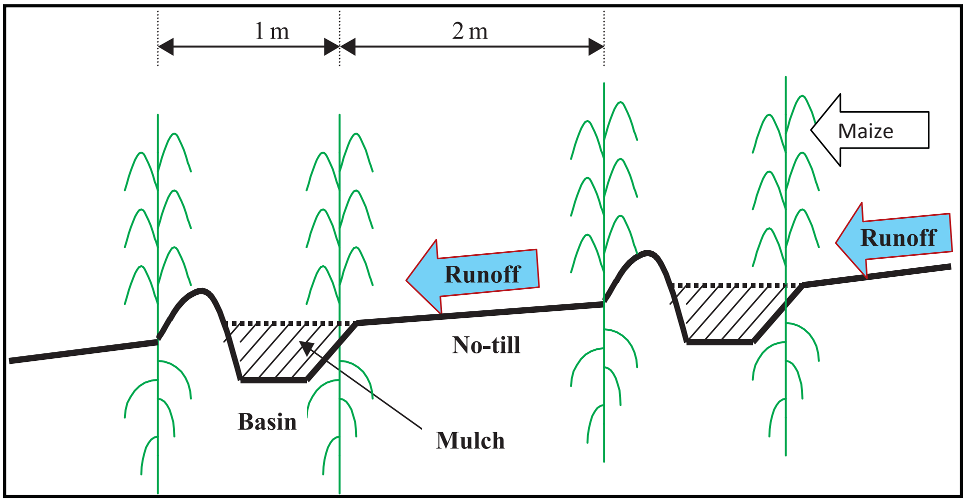

Fig. 1. Diagrammatic representation of the IRWH technique.

Source: Adapted from Hensley et al. (2000).

hydro-ecological and ecosystem services (Andersson et al., 2011).

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 water 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, Rajasthan 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 on the water resource of a river basin.

The Modder River basin, located in the semi-arid regions of central South Africa, is experiencing intermittent 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 recent past, the Institute for Soil, Climate and Water (ISCW) of the Agricultural Research Council (ARC), South Africa, introduced a micro-basin tillage technique which can be used as in situ rainwater harvesting technique. It is also known as infield rainwater harvesting (IRWH). It was developed for small-scale farmers in the basin with the objective of collecting and concentrating of rainwater for crop production (Hensley et al., 2000). It was found that with the use of the IRWH technique (Fig. 1) the surface run-off was reduced to minimum. With this technique, evaporation from the basin soil surface was reduced considerably when mulching is used in the basin. The technique also enhances high water infiltration into the soil by capturing surface runoff in the basin of the IRWH (Figure 1). The technique showed a significant increase in crop yields of maize, sunflower and beans (30–50%) compared to conventional tillage practices at Glen, South Africa (Botha et al., 2003). Makurira et al. (2007) also reported maize yield increase of up to 80% by using a combination of rainwater harvesting and conservation agriculture compared to the conventional tillage practice in Makanya catchment, Tanzania while Ngigi et al. (2006) reported beans, wheat and Maize grain yield increase of 30–150% by conservation tillage compared to the traditional tillage practice in Kenya.

Based on the specific biophysical and socioeconomic requirements of IRWH, some studies were carried out to estimate the suitable areas for IRWH. For instance, Woyessa et al. (2006b) estimated 27% of the upper Modder river basin area as suitable for IRWH based on biophysical conditions. Mwenge Kahinda et al. (2008a,b) estimated 79% of the basin as suitable 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 suitable 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 suitable 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. Most recently, Andersson et al. (2011) assessed the potential impact of in situ water harvesting scenario with other land use scenarios in the Thukela River basin, South Africa, using SWAT hydrological model and reported a non significant impact of the water harvesting technique on the stream flow of the basin. However, this study is aimed at evaluating the impacts of different land use scenarios practiced around the Modder River basin especially, on several streamflow components and water balances of the C52A quaternary catchment simultaneously by applying ArcGIS and SWAT hydrological model.

Numerous modelling approaches have been developed to simulate the impacts 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, especially for ungauged 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; Shimelis et al., 2008; Ouessar et al., 2009; Andersson et al., 2011). 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

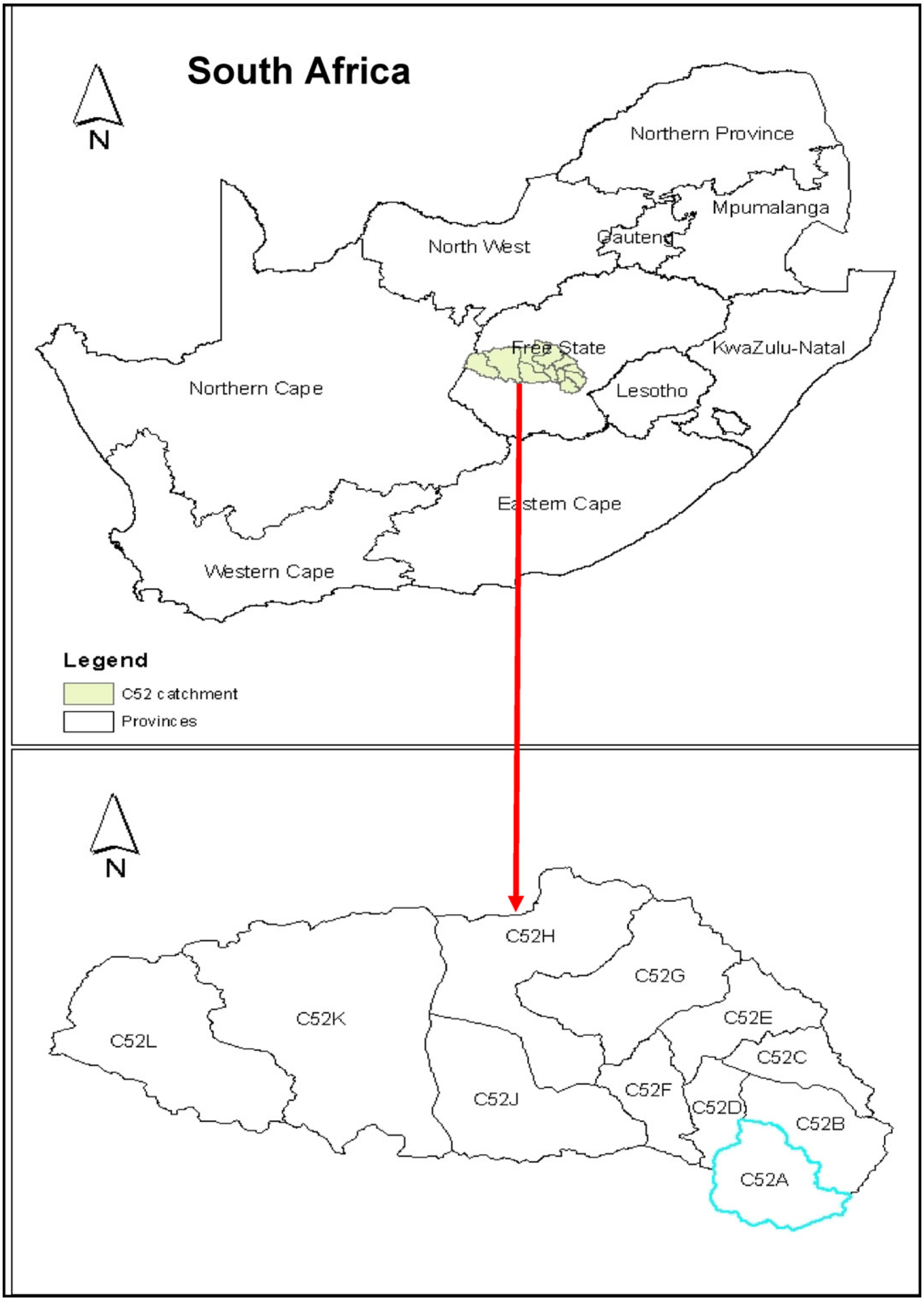

Fig. 2. Location of the Modder river basin (C52) and the study catchment (C52A).

water resources (Fohrer et al., 2001; Chanasyk et al., 2003; Conan et al., 2003b; Mapfumo et al., 2004; Lin et al., 2007; Wei et al., 2008; Choi and Deal, 2008). Similarly, Garg et al. (2011) applied the calibrated and validated SWAT 2005 modelling tool to a community watershed at Kothapally in India to compare the impacts of various soil and water management interventions in the watershed during a 30-year simulation period.

Taking into account its wider application in assessing the impacts 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 changes 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 a tillage technique which is used as in situ rainwater harvesting in the Upper Modder River Basin (C52A) of central South Africa. This research hypothesizes that expansion of IRWH in the upstream of the catchment will have impacts on the different components of catchment streamflow.

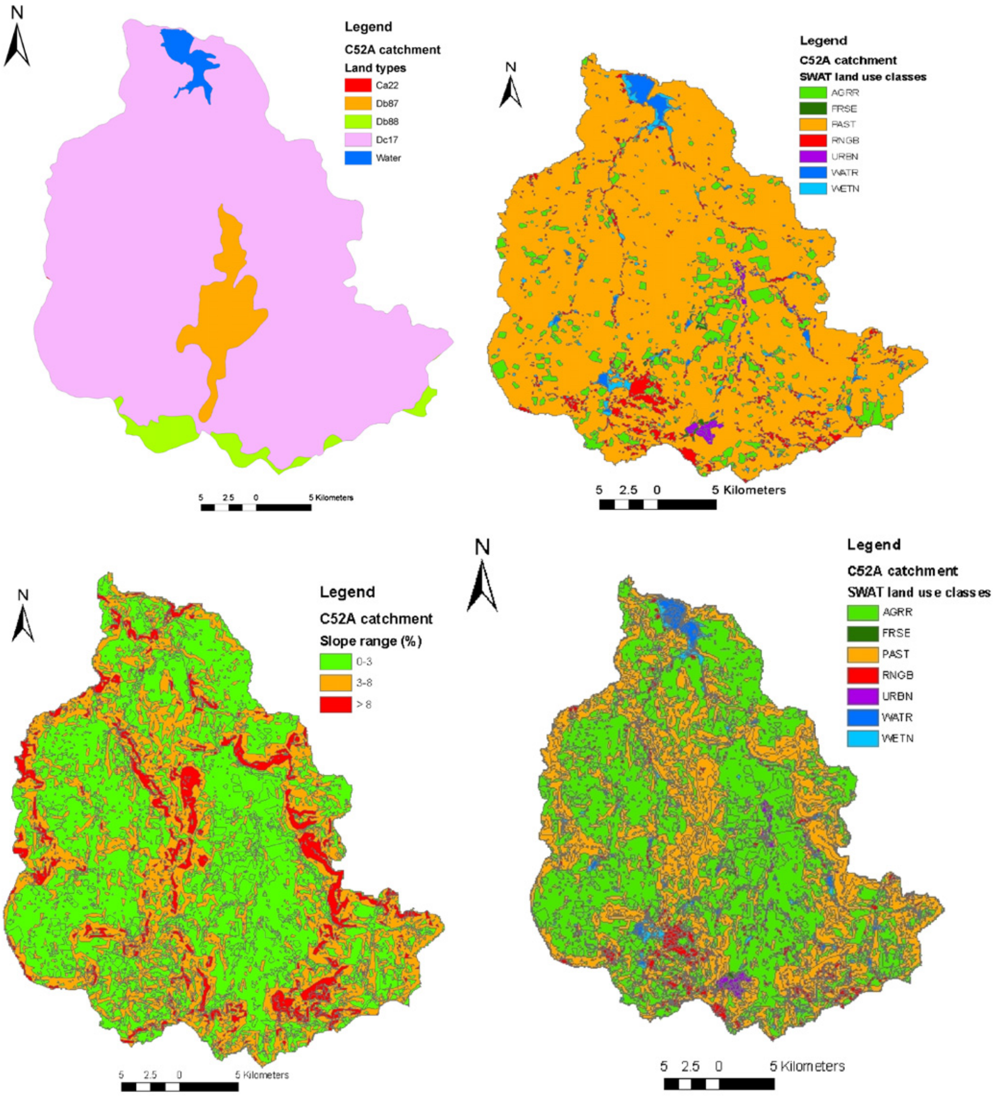

Fig. 3. Soil type, land use and topography of the study site: soil type (a), land use 2000 (b), slope classes (c) and pasture on 0–3% slope changed to agriculture (d). (Note: all land type legends are as defined by Soil Classification Working Group (1991).) The land use classes are defined in Table 1.

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/year and has an area of 927.6 km^2. The dominant soil types of the study catchment are sandy clay loam and sandy clay. According to land use map 2000, the dominant land use type in the catchment is pasture (see Fig. 3b).

2.2. Input data

SWAT model needs land use input data in shape file format or raster format which should be processed from satellite images. The processed shape file data for the year 2000 was obtained from the Institute for Soil, Climate and Water (ISCW) of the Agricultural Research Council (ARC). Other input data needed by SWAT model are as follows:

- Soil type map in shape file.
- Soil data base which includes soil physical and chemical properties for the different soil types in the catchment.
- Climate data (rainfall, minimum temperature, maximum temperature, wind speed, relative humidity, and sun radiation which all can be per day, per month or per year).
- Landscape data in the form of Digital Elevation Model (DEM).
- Basic crop management practices data including type of crop, planting date, tillage type and fertilizer management, etc.

The DEM for the Modder river basin (C52) was obtained from ISCW at a resolution of 90 m × 90 m. Rainfall data at three weather stations in the study basin during 1993–2007 were obtained from South African Weather Service (SAWS) (Fig. 4) whereas temperature data with the same length of records were obtained from SAWS measured at three nearby stations (Bloemfontein-STAD, Bloemfontein-W.O. and Knellport Dam). Other climatic data were generated by SWAT by using WXGEN weather generator model (Sharpley and Williams, 1990). Statistical parameters used in the

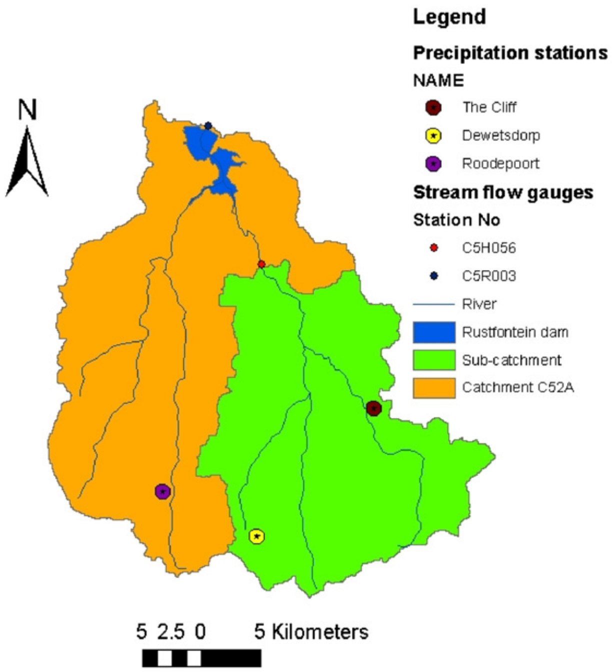

Fig. 4. Study sub-catchment in C52A and locations of rain and streamflow gauging stations.

weather generating module were calculated from 50 years climatic data of C52A catchment (1951–1999) obtained from South African Atlas of Agrohydrology and Climatology developed by Schulze et al. (2001). Rainfall from the three stations was spatially distributed to the catchment sub-basins by SWAT. SWAT uses skewed normal distribution method to calculate rainfall amounts in each sub-basin.

The soil map of the catchment (C52A), in processed shape file format, was obtained from ISCW. The soil of the catchment is covered by land type Dc17 (90.3%) and Db89 (8.3%) (Fig. 3a). Both land types are dominated by Valsrivier soil forms (Soil Classification Working Group, 1991). Therefore, the whole area of C52A catchment was taken as Valsrivir series for this study.

2.3. Model setup

The study was carried out using the comprehensive, semi-distributed and physically based hydrological model, Soil and Water Assessment Tool (SWAT) version 2005. SWAT 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). The SWAT model is primarily developed for ungauged catchments (Arnold et al., 1998). Details of model function and description were given in Arnold et al. (1998). The model was setup using the following input data from the study catchment:

- DEM
- Soil map in shape file
- Land use map of 2000 in shape file
- Rainfall and temperature daily data (1993–2007)

The study area was, then, delineated by SWAT model based on the DEM and the geographic coordinates of the flow gauging station at the outlet of the catchment. As indicated in Fig. 4, there are two gauging stations in the catchment. The gauging station C5R003 measures discharge from the whole area of C52A catchment (927 km^2). The discharge at C5R003 is regulated by Rustfontein dam at the outlet. The second gauging station (C5H056) measures the discharge from a sub-catchment with a contributing area of 412 km^2. The daily streamflow records during the years 2002–2006 for the station C5H056 were obtained from the Department of Water Affairs (DWA) of South Africa. During the delineation process, six sub-basins were created within the catchment C52A.

In this study, land use data of the year 2000 was used as a benchmark against which two land use scenarios were compared. The first parameterization was done based on the land use data of 2000. SWAT uses 27 parameters all of which, except soil parameters, were derived internally by the model during the data input, boundary delineation, and sub-basin and hydrological unit (HRU) creation processes (Arnold et al., 1998). Three slope classes (0–3%, 3–8% and >8%) were used during super-positioning of land use, soil and slope maps to define different HRUs. The slope layer map, which was created by SWAT, was changed to shape file and used as one criterion for creating the different land use scenarios.

Maize agriculture under the conventional tillage and infield rainwater harvesting (IRWH) scenarios were created using 'edit' tool of SWAT and ArcGIS.

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. After parameter calibration, the CN2 under the IRWH scenario was reduced to 35, which is the minimum default value in the model, by using "edit" menu in the SWAT. The change was made in order to reduce the surface runoff to be simulated to minimum. CN2 is the most sensitive parameter which influences the surface runoff in SWAT model (Andersson et al., 2011). Under the conventional scenario, a generic tillage practice was selected to run the simulation while under the IRWH scenario a conservation tillage practice was chosen from the database of tillage practices in SWAT model. Weather data from 1993 to 2007 was used for model set up.

2.4. Sensitivity, calibration and validation

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 (Table 3) by using the auto-calibration module of SWAT. The flow data recorded at the gauging station C5H056 on C52A catchment during the year 2002 was used to calibrate the model's top seven sensitive parameters (Table 3). This was conducted in order to optimize the values of those parameters ranked 1–7 during sensitivity analysis. The calibration module in SWAT calculates only the objective function described as Nash and Sutcliffe efficiency. The objective functions, coefficient of determination (R^2), D-index, residual mean square error (RMSE) were calculated according to Willmott (1981). Model validation was not performed due to unreliable observed flow data beyond the year 2002.

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. During the streamflow simulation process, the first two years data were used to warm up the SWAT model. Once the model was set up and calibrated, the water balance of the catchment was simulated with the SWAT model for each land use scenario. Simulations were conducted on daily as well as on monthly time steps, but the results were interpreted using mean monthly values.

2.5. Scenario definition

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

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

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-case scenario against which the other two scenarios were compared (Fig. 3b and Table 1). To create the first scenario (Agri-CON), a change was made to the original pasture (PAST) land in such a way that the area covered by pasture on slopes of 0–3% was converted to agricultural land (cropped with maize) with conventional tillage practices (Fig. 3c, d and Table 2). The slope ranges were selected in such a way that it satisfies the FAO slope classification standard (FAO, 1990) and the suitable slope range for IRWH (Mwenge Kahinda et al., 2008a). This change brought about a conversion of 420 km^2 (54%) of the pasture area 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 0–3% to an agricultural land planted with maize using an infield rainwater harvesting (IRWH) (Fig. 3c, d and Table 1). In both scenarios, socio-economic factors were not considered as part of a requirement to the land use changes made. Fig. 3c, the slope map and Fig. 3b, the changed land use map shows the spatial area where the change of pasture land to agriculture is made.

2.6. Statistical analysis

Percentage changes of the different streamflow components under the various scenarios from the base-case scenario (PAST) and among themselves were computed using the following formula:

$$\%\,\text{change} = \frac{(\text{Scenario A} - \text{Scenario B})}{\text{Scenario B}} \times 100$$

where A and B are streamflow data generated under the different scenarios.

Besides, statistical test (*F*-test) was conducted to see whether there are significant differences among the scenarios in terms of the generated mean monthly streamflow components.

3. Results and discussion

3.1. Sensitivity analysis and calibration

Streamflow simulations were conducted using SWAT model and the parameters were analysed for their sensitivity on the total streamflow discharge using SWAT's sensitivity analysis module. These are ranked and presented in Table 3. The top ranked parameters has very high influence on the streamflow amount and occurrence spatially as well as temporally.

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 water yield and indicating that the error is not possibly of a systematic nature (Welderufael et al., 2009). The Nash and Sutcliffe efficiency revealed a value of 0.57 for the monthly streamflow calibration, describing a satisfactory correlation between the observed and simulated monthly stream discharges. Fig. 5 shows the plot of observed and simulated streamflow data.

Although the statistical performance was found to be satisfactory on monthly resolution, simulation of the daily streamflow or

Table 2
C52A slope ranges and their 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 sensitive analysis.

Parameter	Rank
Curve number for land use (CN2)	1
Soil available water capacity (Sol_AWC)	2
Threshold depth of water in the shallow aquifer required for return flow to occur (Gwqmn)	3
Soil evaporation compensation factor (Esco)	4
Soil layer depth (Sol_Z)	5
Ground water 'revap[a]' coefficient (Gw_Revap)	6
Soil saturated hydraulic conductivity (Sol_K)	7
Average slope length of sub basin (Slope)	8
Threshold depth of water in the shallow aquifer for 'revap' to occur (Revapmn)	9
Surface lag time (Surlag)	10
Effective hydraulic conductivity in main channel alluvium (Ch_K2)	11
Moist soil albedo (Sol_Alb)	12
Average slope of sub basin (Slsubbsn)	13

[a] *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 for daily stream flow	Value
RMSE	0.18
RMSEs	0.09
RMSEu	0.16
R^2	0.68
D-index	0.86
RMSEu:RMSE	0.87
Nash and Sutcliffe efficiency, NS[a]	0.57

[a] Value for monthly streamflow calibration.

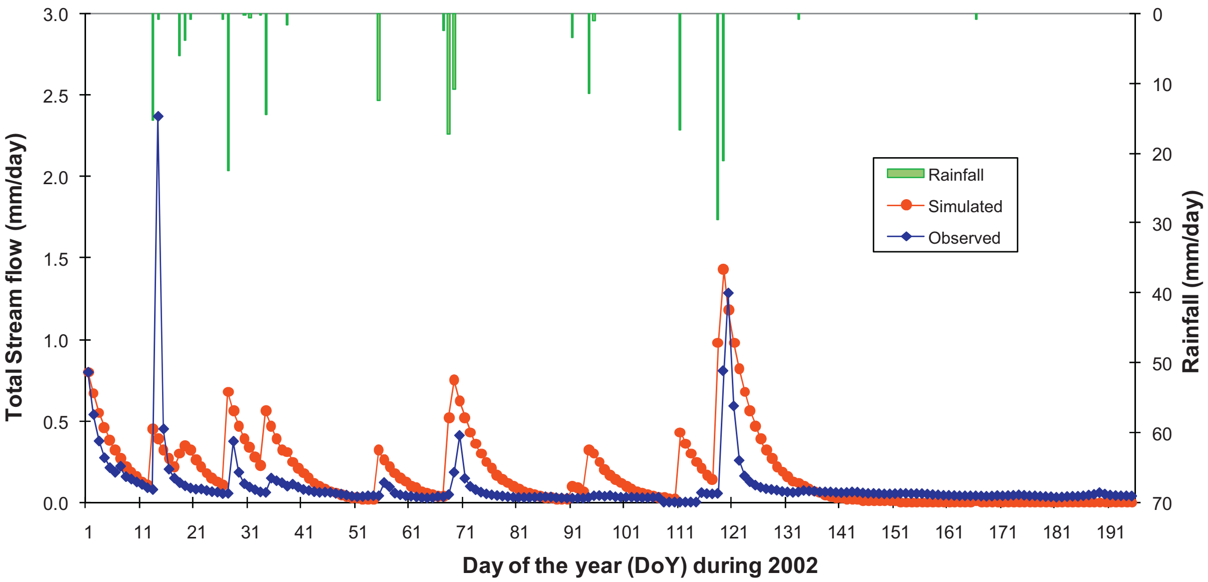

Fig. 5. Observed and simulated daily streamflow (Q) after calibration at gauging station C5H056.

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).

3.2. Water balance of the catchment (C52A)

The impacts of the different land use scenarios on the water balance of the catchment are presented in Figs. 6 and 7 and Tables 5 and 6. The simulated mean monthly water yield (WY = direct flow (DIRQ) + groundwater flow (GWQ)-transmission loss) during the period of 1995–2007 showed non-significant change in peak flow when PAST land on 0–3% slope was converted to Agri-CON and Agri-IRWH land use types. The simulated monthly mean peak WYs were 20 mm/month, 18 mm/month and 16 mm/month 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. 7a). 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 5
Simulated annual deep water percolation under the different land use scenarios.

Year	Precipitation (mm/year)	Annual deep percolation (mm/year)		
		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[a]	39.3[a]	21.7[b]

[a,b] Numbers followed by different letters are significantly different at $P < 0.05$

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. The DIRQ combines surface runoff (SURQ) and lateral flow (LATQ) components. The lateral flow or the interflow is part of the quick response of a streamflow to a rainfall event that infiltrates into the soil and makes its way to the stream channel through the sub-soil above a clayey or semi-impervious layer. Fig. 6a 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/month followed by PAST with 12 mm/month. Agri-IRWH land use scenario generated the lowest DIRQ which amounted to 9 mm/month. Similarly, the mean annual DIRQs were 71, 52, and 45 mm/year under Agri-CON, 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. 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 or insignificant runoff during the whole study period (1995–2007) (Table 5). Ngigi et al. (2006) also estimated the amount of rainfall captured by rainwater harvesting and conservation tillage practices that would have been changed to surface runoff by using a rainfall-runoff model as 50–85%, 75–100% and 100% for heavy, medium and light storms, respectively, compared to traditional tillage which captured and stored 25%, 50–60% and 75–100%, respectively, from similar storms.

Generally, the results of the simulation demonstrated that the annual WY did not show significant difference among the different land use scenarios, which were 89 mm/year, 84 mm/year and 83 mm/year for Agri-CON, PAST and Agri-IRWH, respectively (Fig. 7a). Mwenge Kahinda et al. (2008a) also reported that there was no significant change in the overall WY by the introduction of IRWH in the quaternary catchment C52A. Similarly, Ngigi et al. (2008) after conducting a comprehensive study on the hydrological impact of flood storage and irrigation water abstraction in the

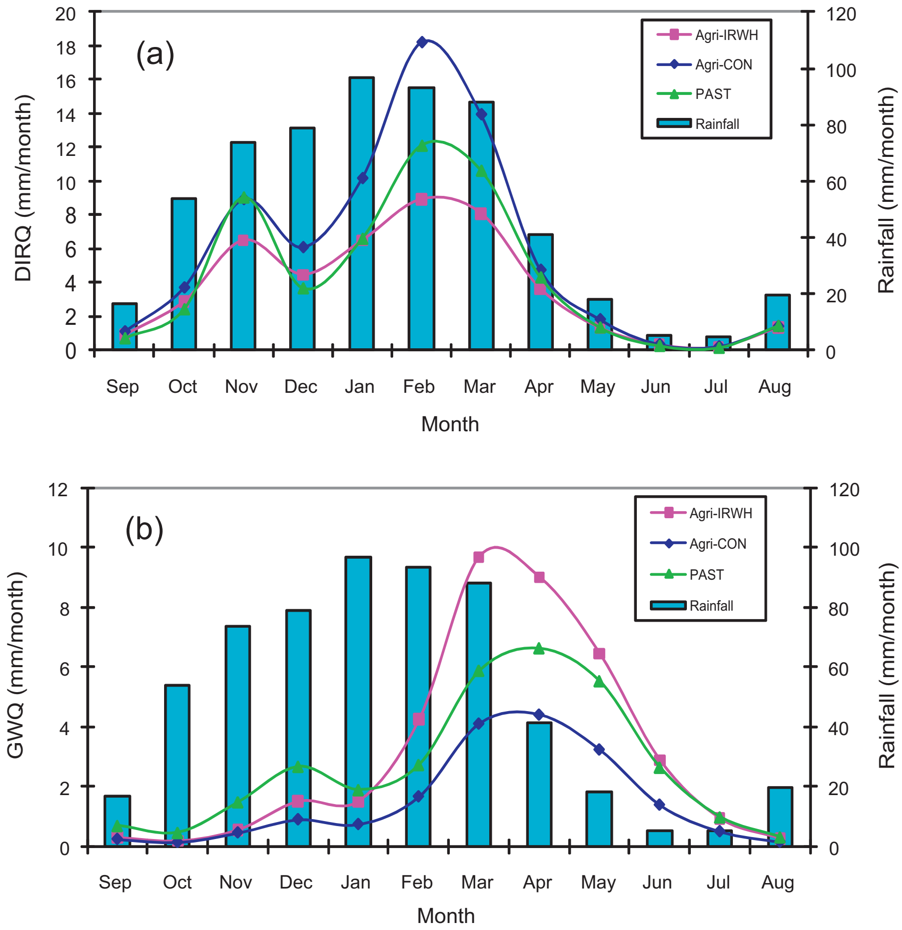

Fig. 6. Simulated streamflow components: (a) direct flow and (b) base flow in the quaternary catchment (C52A) under three land use scenarios.

Upper Ewaso Ng'iro River Basin, Kenya, reported a non-significant effect on the amount of flow downstream.

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. It also showed a 10% increase of the LATQ compared to Agri-CON. This obviously improves the soil water availability within the crop root zone. 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. (2006b) 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. Fig. 6b presents the groundwater flow component of the streamflow. 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

Table 6
Components of the direct flow under the three land uses scenarios in mm/year.

Year	PREC	PAST			Agri-CON			Agri-IRWH		
		SURQ	LATQ	DIRQ	SURQ	LATQ	DIRQ	SURQ	LATQ	DIRQ
1995	590.7	10.6	18.2	28.8	16.5	30.2	46.7	0.0	31.1	31.1
1996	755.5	61.2	27.5	88.6	85.9	42.5	128.4	0.0	51.4	51.4
1997	452.8	8.1	16.0	24.1	12.2	25.6	37.7	0.0	26.6	26.6
1998	811.5	75.1	29.0	104.1	86.5	45.2	131.8	0.0	54.2	54.2
1999	433.0	1.5	12.8	14.3	3.3	22.3	25.6	0.0	22.4	22.4
2000	591.3	6.4	20.4	26.8	10.9	31.4	42.4	0.0	32.1	32.1
2001	934.3	118.8	38.0	156.9	98.3	54.9	153.2	3.9	66.9	70.8
2002	531.3	14.4	18.7	33.1	26.5	29.9	56.2	0.0	32.2	32.2
2003	425.6	19.2	13.5	32.7	23.4	22.3	45.7	0.0	24.1	24.1
2004	403.7	0.1	12.0	12.1	0.7	19.6	20.4	0.0	19.7	19.7
2005	541.9	0.8	16.3	17.1	1.7	25.2	26.9	0.0	25.2	25.2
2006	910.8	104.8	42.4	147.1	112.3	58.2	170.5	0.0	70.4	70.4
2007	396.1	4.1	11.4	15.6	7.0	18.5	25.5	0.0	18.8	18.8
Mean	598.3	32.7	21.2	53.9	37.3	32.8	70.1	0.3	36.5	36.8

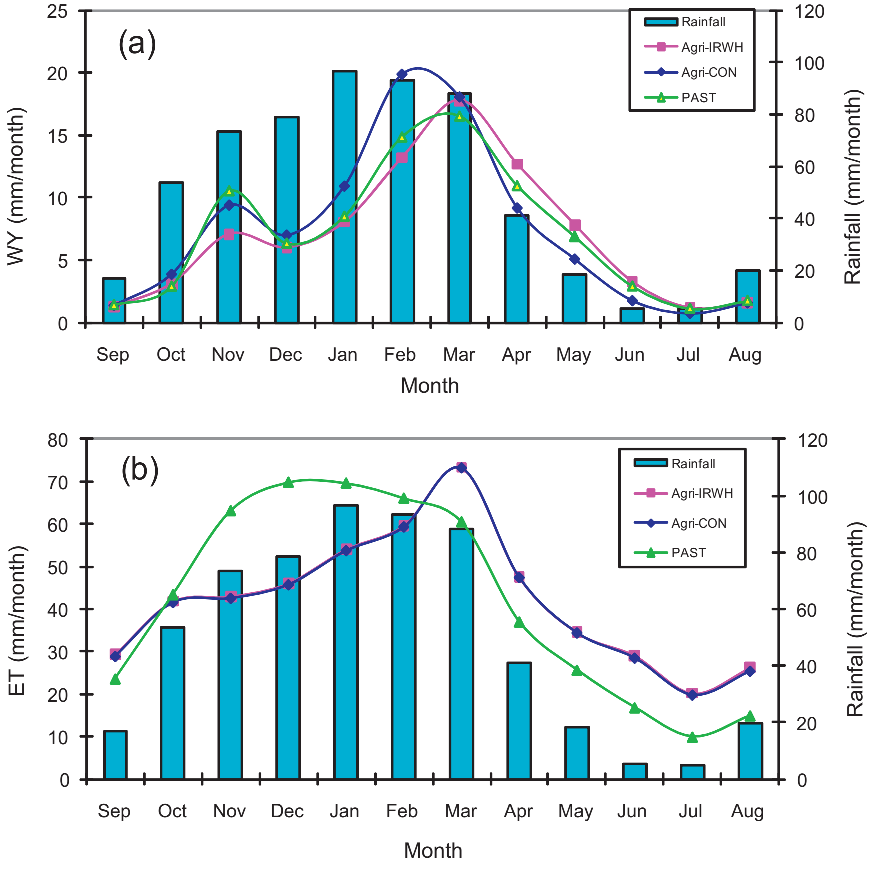

Fig. 7. Simulated water yield (a) and evapotranspiration (b) in the quaternary catchment (C52A) under three land use scenarios.

further deep into the groundwater table than the Agri-CON land use scenario (Table 6). Improved soil infiltration is also reported by Makurira et al. (2009) under rainwater harvesting tillage technique known by *fanya juus* in Tanzania, Makanya catchment. Vohland and Burry (2009) reported that infield rainwater harvesting enhances infiltration and groundwater recharge.

Thus, the Agri-IRWH was found to recharge the groundwater table significantly ($P < 0.03$) more than the Agri-CON scenario. The build up of the water table under the Agri-IRWH 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/month, followed by 7 mm/month and 4 mm/month by PAST and Agri-CON land use scenarios, respectively. The statistical test also showed that there is high 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 Agri-IRWH which was 37 mm/year, followed by 32 mm/year under PAST and 18 mm/year under Agri-CON land use scenarios. The base flow showed an increase of about 105% under Agri-IRWH compared to Agri–CON 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. 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 streamflow during the dry season. This contributes to maintain the environmental flow in the stream as well as provides water downstream 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. 7b). 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.

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 potential 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 implied that there was improvement of water infiltration into the soil by Agri-IRWH land use. Both resulted in higher base flow than Agri-CON land use type and demonstrated increased 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 Agri-CON land use scenario.

Overall, the results suggest that the WY of C52A will 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 the sub-soil physical properties such as soil texture, soil hydraulic conductivity, and soil water holding capacity, which have major influences on the water yield components.

Acknowledgements

The authors would like to acknowledge the financial support received from the Water Research Commission and the National Research Foundation of South Africa.

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