IMPACT OF LAND USE ON WATER RESOURCES OF THE MODDER RIVER BASIN IN 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 abstraction of water in the upstream catchment. Increased water withdrawal at upstream level is an issue of concern for downstream water availability to sustain ecosystem services. The Modder River basin, located 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 objective of harnessing rainwater for crop production. However, the impact of a wider adoption of this technique by famers on the water resources has not been quantified. In this regard, the SWAT hydrological model was used to simulate the impact of such practice on the water resources of the river basin. The scenarios studied were: pasture (PAST), conventional agriculture (Agri-CON) and agriculture using rainwater harvesting (Agri-IRWH). The result showed that the highest mean monthly direct flow was obtained on Agri-CON land use (18 mm), followed by PAST (12 mm) and Agri-IRWH land use (10 mm). The Agri-IRWH scenario reduced runoff by 38% compared to Agri-CON, which justifies its intended purpose. On the other hand, it was found that the Agri-IRWH contributed to more groundwater recharge (40 mm) compared to PAST (32 mm) and Agri-CON (19 mm) scenarios. 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 showed that there was a substantial benefit of using the rainwater harvesting technique for agricultural production (Agr-IRWH) without impacting significantly on the mean annual water yield.

Keywords: Hydrology, catchment, land use, impact, water

1. INTRODUCTION

In a new paradigm shift related to Integrated Water Resources Management (IWRM) in the context of a river basin, attention is being drawn to consider the upstream “off-site” influences on the various water use entities, as well as the downstream impacts arising from them. 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 analysis.

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. This means that the concerns about resources use should transcend short-term “on-site” gains, and should focus on an environmentally sensitive use of resources including many possible “off-site” implications.

Rainwater harvesting is one such activity that involves abstraction of water in the catchment upstream designed for “on-site” gains and may have hydrological impacts on downstream water availability (Ngigi, 2003). Increased water withdrawal at upstream level is an issue of concern for downstream water availability, but it is generally assumed that there are overall gains and synergies to be made by maximizing the efficient use of rainwater at farm level (Rockström, 2001). However, expansion of rainwater harvesting practices could have an unintended hydrological impact on river basin water resources and may have negative implications on downstream water availability to sustain hydro-ecological and ecosystem services.

The excepted 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 (Rockström *et al.*, 2002). The Indian experience, where an Irrigation Department ordered the destruction of community rainwater harvesting structures, fearing that it would threaten the supply of irrigation water to downstream users (Agrawal *et al.*, 2001), indicates the need for further research and understanding on the possible impact of wider expansion of rainwater harvesting technologies for agriculture.

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 purpose. The irrigated agriculture in the basin draws water mainly by pumping out of river pools and weirs. The Krugersdrift Dam, which is located west of Bloemfontein, acts as a buffer for stabilising the water supply to the lower reaches of the Modder River. 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) developed water harvesting techniques for small scale farmers in the basin with objective of harnessing rain water for crop production (Hensley *et al.*, 2000). It has been reported that with the use of the IRWH technique (Figure 1) the surface run-off was reduced to zero and that evaporation from the soil surface was reduced considerably, resulting in a significant increase in crop yield (30-50% yield increases) compared to conventional practices (Botha *et al.*, 2003). The main aim of this paper is to investigate the possible impact of land use practices aimed at harvesting rain water for crop production on the Modder River water balance.

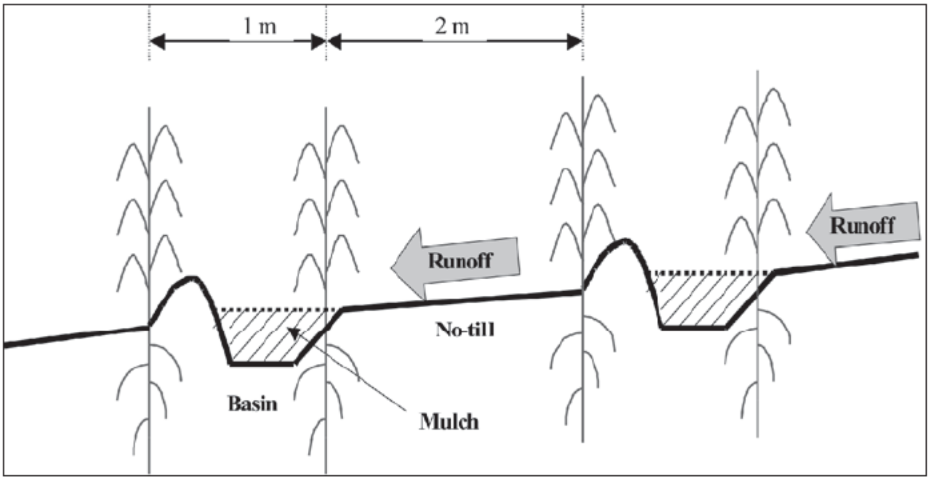


Figure 1. Diagrammatic representation of the IRWH technique (Adapted from Hensley *et al.*, 2000).

2. MATERIAL AND METHODS

2.1 Study area

The Modder River basin is a large basin with a total area of 1.73 million hectares. It is divided into three sub-basins, named as the Upper Modder, the Middle Modder and the Lower Modder. It is located within the Upper Orange Water Management Area to the east of the city of Bloemfontein. The irrigated agriculture in the basin draws water mainly by pumping out of river pools and weirs. However, most of the rural developing farmers rely on rainfed agriculture for crop production. The water supply to the middle and lower reaches of the Modder River is stabilised by the Rustfontein and Mockes dams in the east and Krugersdrift Dam in the west of the city of Bloemfontein.

The study was carried out on the Upper Modder River Basin specifically on the quaternary catchment C52A. It is located between 26.48° and 26.87° East and; between 29.25° and 29.62° South. The catchment has a total area of 927 km^2 and mean annual rainfall of 590 mm. The soil of the catchment is dominated by land type Dc17 which covers approximately 90.3% of the area (Fig. 3a). The other land type found in the catchment is Db87 which covers 8.3% of the catchment area. Water bodies including the Rustfontein dam comprises of 1.4% of the catchment.

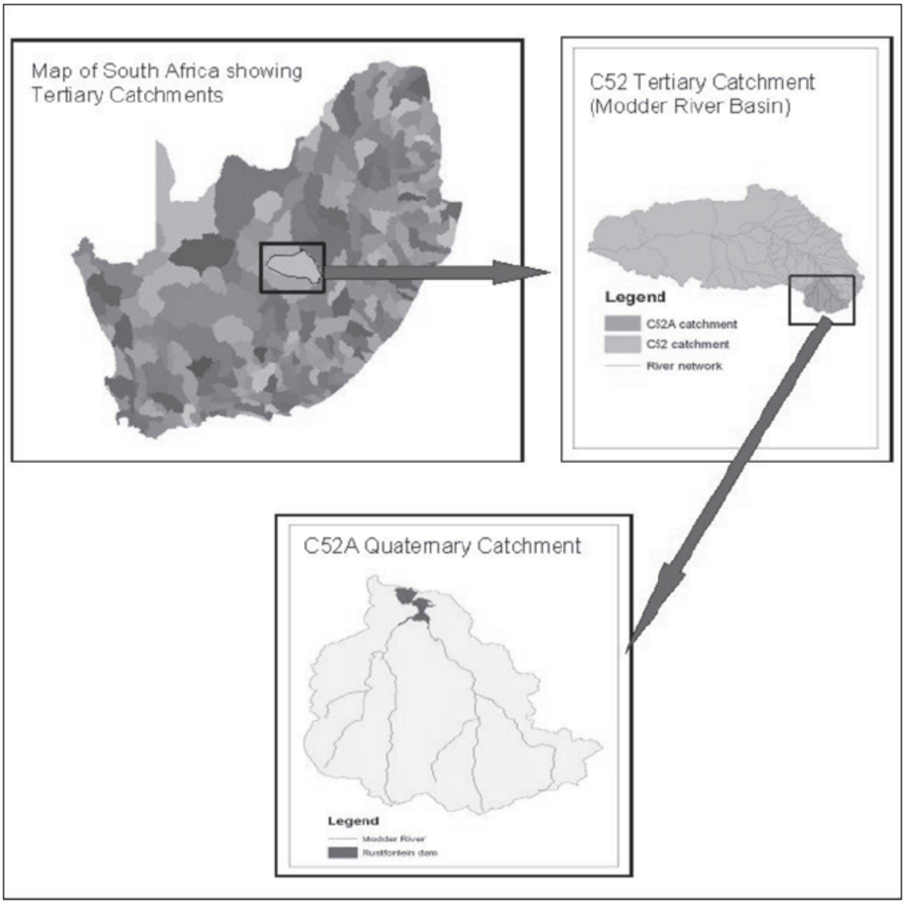


Figure 2. Location of the study area in South Africa and Modder River Basin

2.2 Procedures

Simulation of the water balance components of C52A was carried out by using the ArcSWAT hydrological model (Arnold *et al.*, 1998) which is interfaced with ArcGIS. In this study, land use data for the year 2000 was used as a bench mark against which different land use scenarios were compared. Daily weather data from 1993 to 2007 was obtained from the South Africa Weather Service for three stations within C52A. ArcSWAT model was calibrated using six years of observed stream flow data, from 2002 to 2007. Once the model was calibrated the water balances of C52A was simulated by changing only the land use scenarios. The simulation was done on a daily as well as monthly time step, but the results were interpreted using mean monthly values.

Two land use scenarios were considered: (1) in-field rainwater harvesting based on the work of Hensley *et al.* (2000) which was aimed at improving the precipitation use efficiency (PUE) and (2) conventional land use which represents the current land use practice in the area. 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. 3a 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 land on slopes of 0 to 3% was converted to agriculture with conventional practices (Fig 3d and Table 2). This change brought about 420 km^2 (54%) of the pasture area on slopes of 0-3% under agricultural land. This has increased the area of the agricultural land from 8% to 53% and decreased 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 scenario and they both have the same area of crop land and crop type which is maize, the only difference being the tillage type, i.e. scenario-1 uses conventional row cropping while scenario-2 uses IRWH.

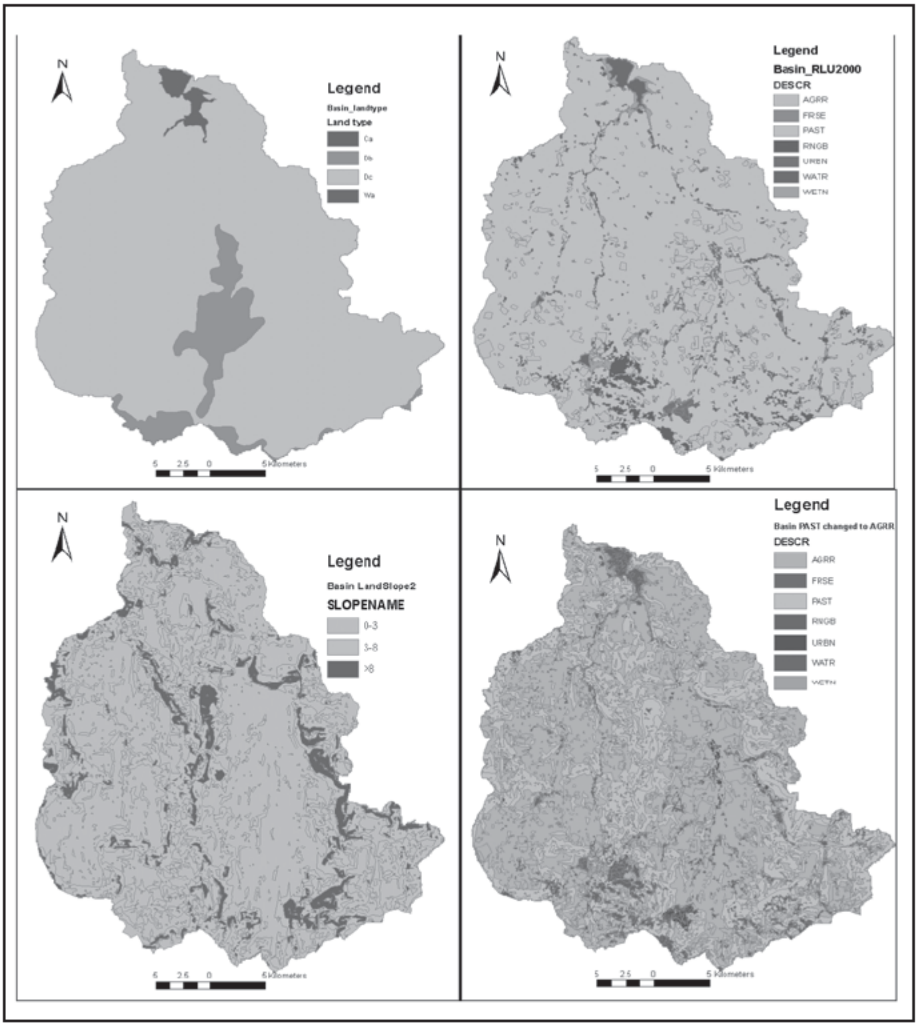
The curve number for antecedent moisture condition (CN2) and tillage management were modified for Agri-IRWH in order to satisfy the surface condition created by IRWH. The change of land use from pasture to maize conventional planting and IRWH was done by ArcGIS. The slope ranges were selected in such a way that it satisfies the FAO slope classification standard and the suitable slope range for IRWH (Kahinda et al., 2008).

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

Land use type	**Area & percentage**		**Area & percentage under Agri-CON or Agri-IRWH**	
	Area (km^2)	(%)	Area (km^2)	(%)
Agriculture (AGRR)	72.4	7.81	492.4	53.11
Ever green forest (FRSE)	2.2	0.24	2.2	0.24
Pasture (PAST)	780.0	84.12	360.0	38.83
Range plus brush land (RNGB)	42.0	4.53	42.0	4.53
Urban (URBN)	6.1	0.66	6.1	0.66
Water bodies (WATR)	10.5	1.13	10.5	1.13
Wet land (WETN)	14.0	1.51	14.0	1.51
Total	**927.2**	**100.00**	**927.1**	**100.00**

Table 2. C52A slope ranges and area coverage

Slope range (%)	**Area (km^2)**	**(%)**
0 - 3	524.1	56.53
3 - 8	319.0	34.41
> 8	84.0	9.06
Total	**927.1**	**100.00**



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

3. RESULTS AND DISCUSSION

The impacts of the different land use scenarios on the components of the stream flow are presented in Figure 4. The mean monthly water yield (direct flow plus base flow) for the period of 1993 to 2007 showed significant differences in peak flow when pasture (PAST) land on 0 to 3% slope was converted to Agri-CON and Agri-IRWH land uses. The monthly mean peak water yields were 20 mm, 18 mm and 16 mm for Agri-CON, Agri-IRWH and PAST, respectively.

The mean monthly water yield on the Agri-CON land use scenario was higher than the other two scenarios during the rainy months of December to March only (Figure 4a). During the remaining months, the two land use types (Agri-IRWH and PAST) recharged ground water better and had more water yields than the Agri-CON land use scenario. Agri-IRWH showed a higher peak flow value than PAST probably due to the high ground water contribution by the IRWH technique during the same month as the occurrence of the peak flow.

The effect of the different land use scenarios on the water balance of C52A is well demonstrated by the direct runoff component of the water yield. The direct runoff comprises the surface runoff and the lateral flow, also known as interflow. Figure 4a presents the direct flow component of the three land use scenarios. The highest mean monthly peak flow was obtained on Agri-CON land use, amounting to about 18 mm followed by PAST with 12 mm. Agri-IRWH land use scenario generated the lowest direct flow amount of about 10 mm. Similarly the mean annual direct flows were 53, 72, and 45 mm on PAST, Agri-CON and Agri-IRWH land use scenarios, respectively. Generally, the results of the simulation demonstrated that the total annual water yield was affected minimally by the different land use scenarios, which were 91 mm, 85 mm and 84 mm for Agri-CON, Agri-IRWH and PAST, respectively. Kahinda *et al.* (2008) also reported that there was no significant water yield change by the introduction of IRWH in the quaternary catchment C52A.

As per its intended purpose, Agri-IRWH reduced the direct surface runoff by 38% compared to the Agri-CON land use scenario. This obviously improves the soil water availability within the crop root zone as well as the 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; Botha *et al.* 2007). Woyessa et al. (2006) also reported that Agri-IRWH improved both crop production and monetary income of a farmer more than Agri-CON 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 ground water (base flow) component of the water yield in C52A. Figure 4a presents the ground water discharge to the stream flow. Agri-IRWH, due to its surface runoff harnessing design, collects the runoff generated from the 2 meter strip and stores it in the basin (Figure 1). By doing so it allows more water to infiltrate into the soil and to percolate further deep into the ground water table than the other two land use scenarios (Table 3).

Table 3: Simulated annual deep water percolation on the different land use scenarios

Year	Precipitation (mm)	Annual deep percolation in 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**^{a}	**39.3**^{a}	**21.7**^{b}

^{a} = numbers followed by different letters are significantly different at $P < 0.05$

Thus, the Agri-IRWH was found to recharge the ground water table better than the other two scenarios. The build up of the water table under the Agri-IRWH will in turn contribute to the recharge of the stream of C52A as a base flow. Thus, the highest mean monthly peak ground water flow was produced by Agri-IRWH amounting to 10 mm, followed by 7 mm and 5 mm by PAST and Agri-CON land use scenarios, respectively. The annual mean ground water flow was also found to be the reverse of the direct flow. The highest annual ground water flow was obtained from Agri-IRWH which was 40 mm, followed by 32 mm on PAST and 19 mm on Agri-CON land use scenario. The base flow showed about 105% increase on Agri-IRWH compared to Agri-CON land use scenario. The results demonstrate that there was high infiltration of water on Agri-IRWH and PAST than on the Agri-CON land use. 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 water yield peak flows. This may have positive environmental as well as hydrological implications/impacts downstream.

With regard to 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. 7d). The ET from Agri-CON and Agri-IRWH land use followed the same pattern due to the same type of crop (maize) considered in both cases. The annual ET of Agri-IRWH showed a 4 mm more water loss than both Agri-CON and PAST land use scenarios.

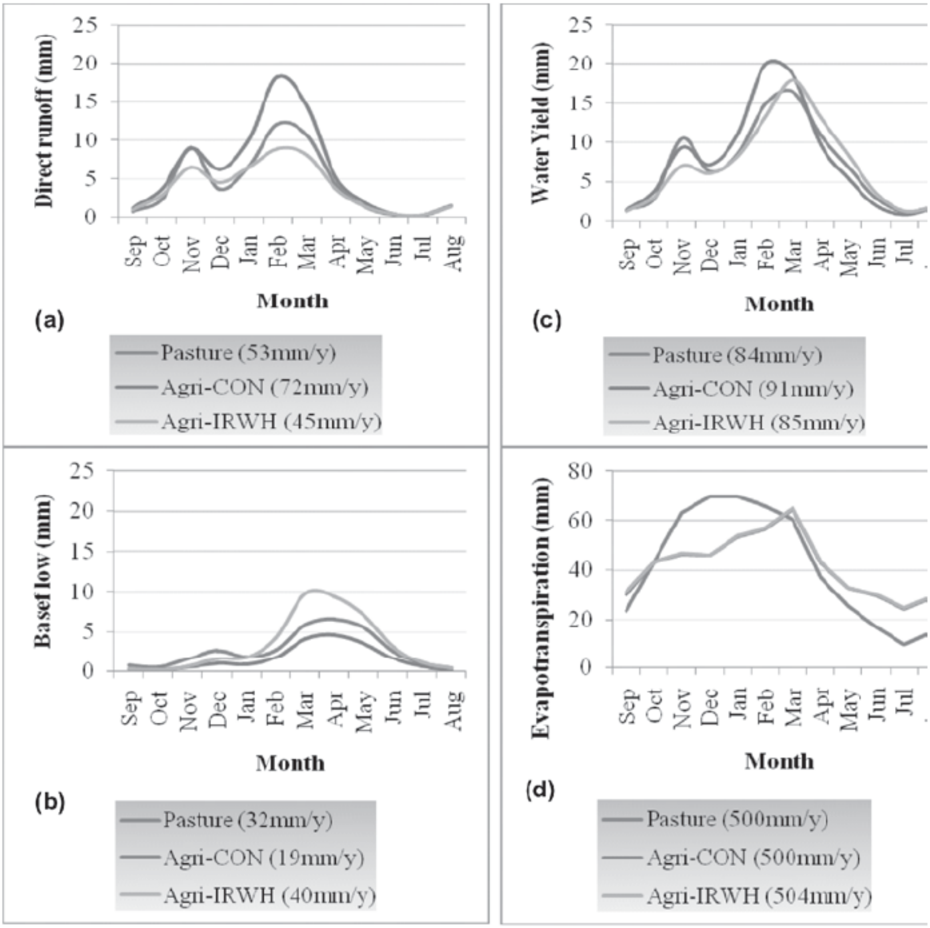


Figure 4. Water balance components of catchment C52A for three land use scenarios: Direct flow (a); Base flow (b); Total water yield (c); and Evapotranspiration (d)

4. CONCLUSIONS

The result revealed that conventional agricultural land use generates highest direct flow than the ones covered by pasture or IRWH land use. This may not support favourable crop production on rain-fed 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. However, it is difficult to conclude whether the increased direct runoff would have been more beneficial if it was to be harnessed by small ponds or dams on-site for use as a supplemental irrigation using the Agri-CON production scenario or if used by the downstream communities from the increased stream flow.

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

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