Up-scaling of rain-water harvesting for crop production in the communal lands of the Modder River basin in South Africa: Comparing upstream and downstream scenarios

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Abstract

The study area is the Upper and Middle Modder River basin situated in a semi-arid area of central South Africa. This is an important catchment because of the relatively large nearby towns of Bloemfontein, Botshabelo and Thaba Nchu. Crop production in the basin using conventional production techniques is currently not suitable due to marginal and erratic rainfall, and high evaporative demand, as well as low precipitation use efficiency on the clay and duplex soils caused by large runoff and evaporation losses. A labour-intensive in-field rain-water harvesting (IRWH) technique for crop production recently introduced into a part of the basin occupied by communal farmers has been shown to increase maize and sunflower yields by 30 to 50% compared to conventional tillage, making crop production utilising this technique a feasible proposition for these farmers. The area of land suitable for the IRWH in the basin is estimated to be 80 667 ha, of which 15 000 ha is located in the communal land. The two catchment management options compared in this paper are:

- Allowing the 80 667 ha to remain under grassland and utilising the runoff downstream for irrigating maize
- Utilising the 80 667 ha for maize production in the basin using the IRWH technique.

Results showed that the expected maize production from the options shown above were 23 040t and 137 134t respectively. The large unproductive water losses during storage and conveyance to downstream use points are probably the main reason for this large difference in production. An economic analysis, which enabled the grazing benefit to be included in the first option, shows that the gross margin of this option, expressed as R/m^3 of rain water utilized, could be expected to be between 0.0234 to 0.0254 under current conditions, of which irrigation contributed about 25% or less. The comparable value for the IRWH option was 0.0354. The second option is clearly shown to be the most preferable, with high socio-economic benefits for the communal farmers who are currently struggling to achieve sustainable livelihoods.

Keywords: rain-water harvesting, catchment management, river basin, small-scale farming

Introduction

In a new paradigm shift related to integrated water resource management (IWRM) in the context of a river basin, attention is being drawn to consider the upstream ‘on-site’ influences on the various water use entities, as well as the downstream ‘off-site’ impacts arising from them. Along the path of water flowing in a river basin are many water-related human interventions, including water storage, diversion, regulation, distribution, application, pollution, purification and other associated acts to modify the natural systems. All of these have one common effect, and that is that they impact on those who live downstream (Sunaryo, 2001). This concept of river basin analysis of water would enhance the common understanding of the issues on overall productivity of water, such as in rain-fed agriculture and related strategies.

Green water productivity in rain-fed agriculture will have to increase dramatically over the next generations if food production is to keep pace with human population growth (Rockström et al., 2002). In sub-Saharan Africa, over 60% of the population depends on rain-based rural economics, generating about 30 to 40% of the regions’ GDP (World Bank, 1997). Rain-fed agriculture is practiced on approximately 95% of agricultural land, with only 5% under irrigation (Rockström et al., 2002). This shows that rain-fed agriculture will remain the dominant source of food production for the foreseeable future in sub-Saharan Africa.

In many parts of the water-scarce countries, yields from rain-fed agriculture are low, oscillating around 1 t·ha^{-1} (Rockström, 2001). However, many researchers suggest that the low productivity in rain-fed agriculture is more due to sub-optimal performance related to management aspects than to low physical potential. For instance, Bennie et al. (1994) reported that in arid and semi-arid areas between 60 and 85% of the rainfall evaporates from the soil surface before making any contribution to production.

A reduction in runoff will result from practices that successfully increase the infiltration capacity of the soil, increase the contact time, and/or reduce surface sealing. It is commonly accepted that covering the soil with a mulch, for example, with a crop residue, will achieve these goals (Unger, 1990) and will also reduce evaporation from the soil surface. The infield rain-water harvesting technique, whereby runoff is captured in a micro-basin, is found to reduce runoff from the field to zero (Hensley et al., 2000) by converting to stored soil water, leading to increased

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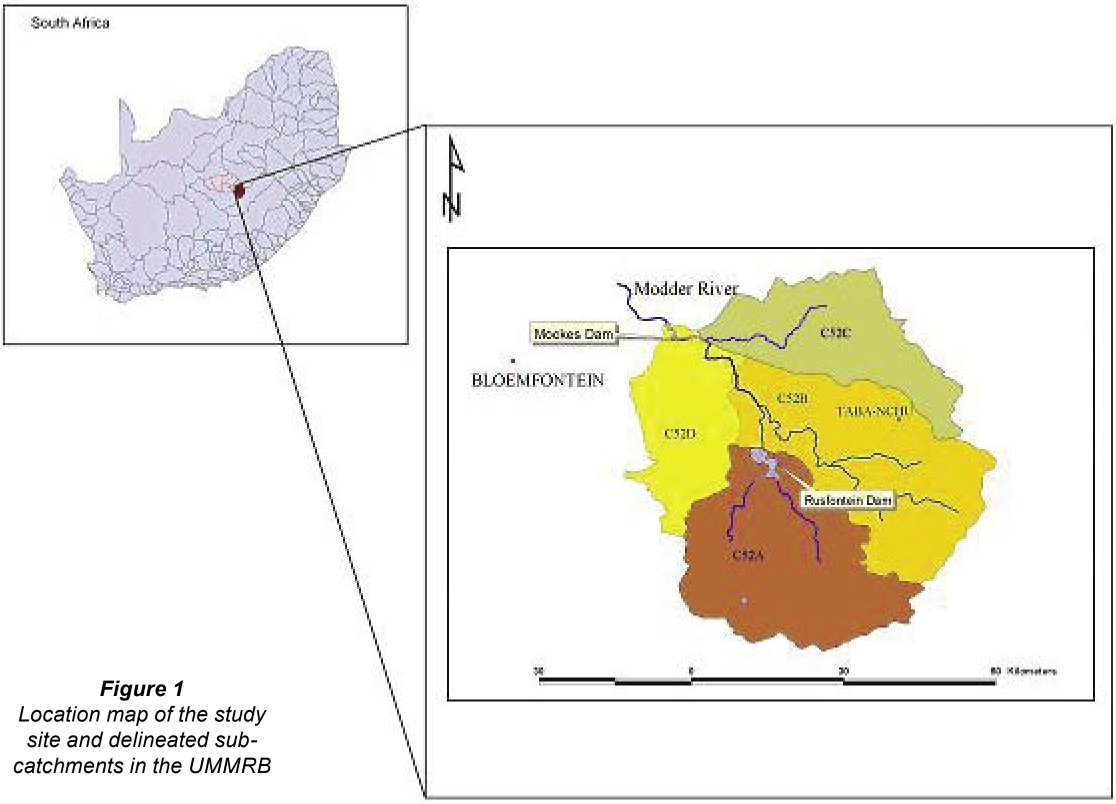

Figure 1
Location map of the study site and delineated sub-catchments in the UMMRB

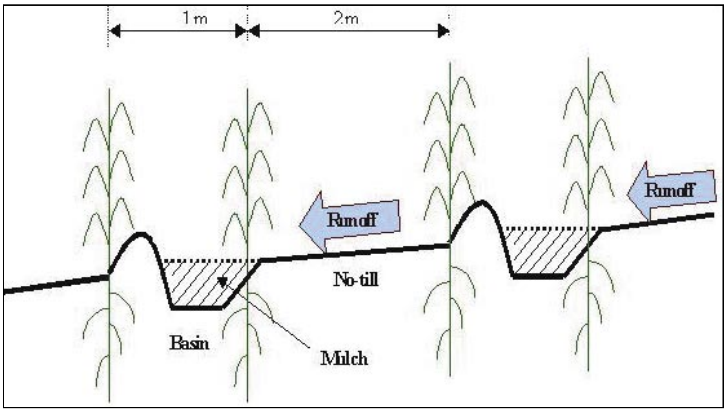

Figure 2
Diagrammatic representation of the infield rain-water harvesting (IRWH) crop production technique (adapted after Hensley et al., 2000)

yields, compared with conventional tillage.

With the use of the IRWH technique runoff and soil loss from the cropland were reduced to zero (Hensley et al., 2000). It is also reported that the use of mulch in the basins reduced evaporation significantly, contributing to the increase in yield, on average 30 to 50%, compared to production under conventional tillage (Hensley et al., 2000; Botha et al., 2003). On the other hand, it has been shown by several hydrological studies at watershed level that upstream shifts in water-flow partitioning may result in complex and unexpected downstream effects, both negative and positive, in terms of both water quantity and quality (Vertessy et al., 1996; cited by Rockström et al., 2002).

In South Africa, irrigated agriculture takes place on 1.3×10^6 ha of land (almost 10% of the total cultivated area) and uses an estimated 12.3×10^9 m^3 of surface and groundwater per year, which is about 56% of the country's total annual water use (WRC, 2000). Irrigated agriculture draws water mainly from dams and water transfer schemes between catchments on which the retention of sufficient runoff has been ensured (Beukes et al., 2004). In the study area, there are two dams (Fig. 1), namely Rustfontein Dam and Mockes Dam that store water for the supply of potable water to the cities of Bloemfontein, Botshabelo and Thaba Nchu and also for the supply of irrigation water for the downstream commercial farmers. Wide-scale adoption of the IRWH technique (Fig. 2) could have an impact on the quantity and quality of water downstream of the river basin if it is applied on all the suitable lands in the basin. The objective of this paper is to present results of an assessment of this possible impact. It includes the impact on runoff generation and inflow into the dams that are located in the study area; the different options of rain-water use, i.e. upstream ('on-site') and downstream ('off-site') scenarios are also considered.

Methodology

The Modder River basin is a large basin with a total area of 1.73×10^6 ha. It is divided into three sub-basins, namely the Upper Modder, the Middle Modder and the Lower Modder. It is located within the semi-arid Upper Orange Water Management Area to the east and north of the city of Bloemfontein, central South Africa. Four quaternary catchments, hereafter referred to as sub-catchments, located in the Upper and Middle Modder River Basin (UMMRB) have been selected for this study (Fig. 1). These sub-catchments are: C52A, C52B, C52C and C52D with a total area of 294 445 ha.

Long-term data on the hydrology of the catchment, such as precipitation and runoff were obtained from a database of sur-

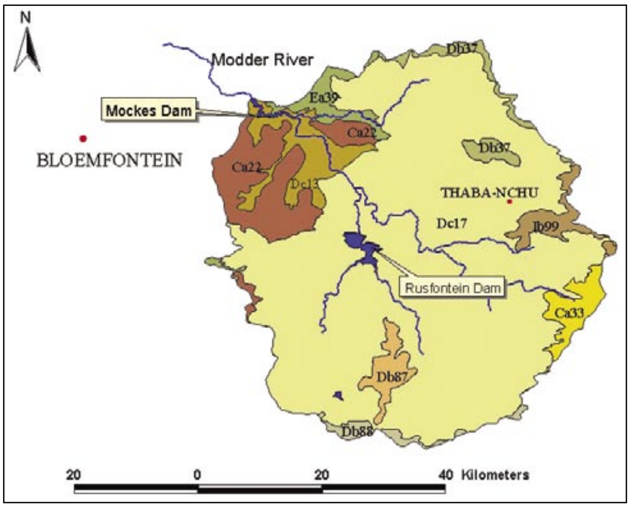

Figure 3
Map of the study area showing the land type codes, such as Dc17, Ca22, etc.

TABLE 1
Land types and area of land in the catchment suitable for the IRWH technique

Land Type	Total area (ha)	Estimated area for IRWH (%)	Estimated area for IRWH (ha)	Main soil types[a]
DC17	224 052	24	53 772	Sw, Se, Va, Ar, Be,
Ca22	23 335	60	14 001	Va, We
Ca33	6 637	65	4 314	We, Ss
Db37	6 118	15	918	Va, Sw
Db87	5 418	35	1 896	Va, Sw, Ss
Dc13	13 499	25	3 375	Va, Oa
Ea39	6 528	20	1 306	Ar, Mw, Va
Ib99	5 759	0	0	Ms, Rock
Db88	3 099	35	1 085	Ss, Va, Sw
Total	294 445	27.2	80 667	

[a] Main soil types are: Va = Valsrivier, We = Westleigh, Ss = Sterkspruit, Oa = Oakleaf, Ar = Arcadia, Mw = Milkwood, Ms = Mispah, Bo = Bonheim, Sw = Swartland

face water resources of South Africa (Midgley et al., 1994). Identification of the suitable area of land for the IRWH technique in the study area was done based on soil and topographical information (Tekle et al., 2004). Following the results of six years of field research on IRWH on different soils and resultant guidelines proposed by Botha et al. (2003), it was decided that duplex and clay soils of at least 700 mm deep and slopes of less than 3% would be considered suitable for growing maize and sunflower using the IRWH production technique. The different land types in the study area and the estimated area of suitable land for the IRWH are given in Fig. 3 and Table 1 respectively. The mean annual runoff was estimated for the whole catchment and the possible impact of the IRWH technique on runoff generation was quantified. Comparative analysis of the use of rainfall for crop production was made for 'on-site' (upstream) and 'off-site' (downstream) conditions comparing the total production and gross margin per unit amount of rain water, i.e. water productivity (Molden et al., 2003). The expression of water productivity in this case is given in terms of monetary value per unit amount of rain water.

Results and discussion

Impact of the IRWH technique on runoff generation

The runoff generated from C52A, one of the sub-catchments in the study area, is captured by the Rustfontein Dam. The remaining sub-catchments, such as C52B, C52C and C52D drain into the Mockes Dam. Gauging stations placed in the vicinity of the two dams measure the incoming runoff water into these dams. For the Rustfontein Dam these data are available for 36 years giving the mean annual total runoff flowing into this dam as 27.9 x 10^6 m^3 (Midgley et al., 1994) from a catchment area of 93 700 ha (i.e., area of C52A).The mean annual precipitation for the study area is 537 mm. Based on these values the mean runoff coefficient was calculated to be 5.95%, which is similar to the values obtained at experimental sites on conventional plots (total soil tillage) at Glen Experimental Station (Hensley et al., 2000).

Using the above information, the runoff amount draining into the Mockes Dam can be estimated. The catchment draining into the Mockes Dam (C52B, C52C, and C52D) has a total area of 202 066 ha. The mean annual runoff flowing into the Mockes Dam is therefore estimated at 68.6 x 10^6 m^3. Table 2 shows possible scenarios of what may be expected if all the suitable land in the catchment is put under cultivation using the IRWH technique. The aim of this exercise is to see the extent to which the inflow into the dams may be affected under this extreme scenario. The area of land suitable for the IRWH technique, based on soil type and topographical features, is estimated to be 80 667 ha. If all the runoff from this portion of the catchment were to be retained for on-site use for crop production using the IRWH technique, it is estimated that it will reduce the mean annual runoff from 94.42 x 10^6 m^3 to 68.67 x 10^6 m^3, i.e. a reduction of 25.75 x 10^6 m^3. It should be noted that, in this part of the country, mean annual evaporation (Class A pan) is 2 198 mm (Botha et al., 2003) which can cause a tremendous amount of water loss from dams, rivers and other storage reservoirs. For instance, with the storage surface area of Rustfontein Dam of 1 158.5 ha, it is estimated that 25.5 x 10^6 m^3 of water could be lost annually through evaporation. This is one of the water losses that can be avoided by the on-site use of rain water for food production at

TABLE 2
Estimated runoff and possible impact of the IRWH technique on the inflow of runoff into the dams

Parameters	Unit	Values
Mean annual precipitation	mm	537
Average runoff coefficient	%	5.945
Total area of the catchment (i.e. C52A-D)	ha	295 766
Total suitable area for the IRWH technique	ha	80 667
Suitable area as % of the total area of the catchment	%	27.2
Estimated mean annual runoff from the total area	m^3	94.42 x 10^6
Mean annual runoff retained in the IRWH area	m^3	25.75 x 10^6

TABLE 3

Water budget to compare how rainfall in a part of the UMMRB is utilized by two agricultural production strategies (storage plus conveyance losses are assumed to be 35% and 60% for Scenarios A and B respectively)

Production Strategy	Parameters	Units	Values	
			Scenario A	Scenario B
Irrigation	- Total area of land suitable for IRWH	ha	80 667	80 667
	- Mean annual runoff retained by IRWH	m^3	25.75 x 10^6	25.75 x 10^6
	- Water losses (storage plus conveyance)	m^3	9.01 x 10^6	15.45 x 10^6
	- Water available at field for irrigation	m^3	16.74 x 10^6	10.30 x 10^6
	- Water demand for a target yield of 10 t maize·ha^{-1}:			
	• Rainfall (50% effective) Nov-Mar	mm	190	190
	• Irrigation water (I)	mm	545	545
	• Total demand[a]	mm	735	735
	- Gross irrigation water demand with centre-pivot system	mm	726.67	726.67
	[(I x 100)/75]·ha^{-1}	m^3	7 266.7	7 266.7
	- Irrigable area with the available water	ha	2 304	1 417
	- Expected maize grain production at 10 t·ha^{-1}	kg x 10^3	23 040	14 170
Veld grass production	- Total grass[b] produced at 1.3 t·ha^{-1} from 80 667 ha	kg x 10^3	104 867	104 867
IRWH	- Maize grain production at 1.7 t·ha^{-1} from 80 667 ha using IRWH[c]	kg x 10^3	137 134	137 134

[a] (Bennie et al., 1988); [b] (Snyman, 1998); [c] (Botha et al., 2003)

the upstream level.

However, the assumption of the scenario of all the suitable land for IRWH being put under cultivation using the IRWH technique should be seen in relation to the following factors:

- Firstly, the current form of the IRWH technique has been designed for implementation using hand labour, and therefore is only suitable for the relatively small areas expected to be developed initially by communal farmers living in the catchment area. The estimated area of suitable land for the IRWH technique inhabited by communal farmers is 15 000 ha. At present the IRWH technique is employed almost exclusively by large numbers of the communal farmers in their backyard gardens. The rate of expansion into the 15 000 ha of communal cropland is expected to be determined by the extent and rate at which certain socio-economic constraints can be overcome.
- Secondly, research is currently being planned to mechanize the IRWH technique and make it suitable for commercial production. If this proves to be successful, expansion would probably be accelerated. The technique may then even be employed by the commercial farmers on the remaining 65 667 ha of land in the catchment suitable for the IRWH technique.

Under present conditions, it is clear that expansion of the technique into the entire suitable area is far from imminent. There is therefore no reason to believe that the water balance of the Modder River will soon be affected significantly due to the expansion of the IRWH technique. However, it is useful to study the possible impact of the different scenarios of rain-water use, namely 'on-site' vs. 'off-site', in relation to the comparative advantage in terms of yield, green water productivity and economic factors. These are discussed in the following section.

Crop production scenarios and water productivity: 'on-site' vs. 'off-site'

There is a growing need for wise catchment management decisions in the whole of South Africa in general and the Modder River basin in particular, because water is such a limiting factor. This need has been recognized in the new National Water Act by the creation of catchment management agencies (CMAs) (DWAF, 2004). This paper presents the information required by a hypothetical CMA to make a wise decision regarding rainwater management and utilization at a catchment level.

The catchment management question can be formulated as follows:

Which of the following two strategies will result in the wisest use of the rainfall which falls on an important portion of the UMMRB?

- Allowing the 80 667 ha (IRWH suitable area) to remain under grassland and utilising the runoff to flow via storage dams and be used downstream for irrigation (off-site).
- Utilising all the rainfall on the 80 667 ha for growing maize (or sunflower) using the IRWH technique (on-site).

Data are presented in Tables 2, 3 and 4 to facilitate the relevant catchment management decision.

Values of critical importance in the calculations are the losses from the original runoff water which occur due to:

- Evaporation from the storage dams
- Transmission downstream between the two dams, and further downstream below Mockes Dam to the hypothetical irrigation site

Reliable values for these parameters are currently not available. As a preliminary solution to this difficulty, two scenarios are presented in Table 3, using two fairly extreme values for storage and conveyance losses, i.e. 35% (Scenario A) and 60% (Scenario B). For irrigation purposes a centre-pivot system with 75% efficiency was assumed. The total water requirement for a target yield of 10 t maize grain·ha^{-1} was estimated to be 735 mm (Bennie et al., 1988).

It has been reported that crop production in the study area under dry-land and conventional tillage is marginal because of relatively low and erratic rainfall and predominantly duplex and clay soils on which the precipitation use efficiency is low due to large runoff and evaporation losses from the soil surface

TABLE 4
An economic assessment of the two production strategies and scenarios described in Table 3

Production Strategy	Parameters	Unit	Scenario A	Scenario B
Irrigation plus veld grazing	- Irrigable area with the available water	ha	2 304	1 417
	- Expected maize production at 10 t·ha^{-1}	t	23 040	14 174.2
	- Gross income @ R700·t^{-1} for maize	R	16.13 x 10^6	9.92 x 10^6
	- Allocatable cost @ R6 000·ha^{-1}	R	13.82 x 10^6	8.50 x 10^6
	- Gross margin from irrigation on 2 303.66 ha	R	2.31 x 10^6	1.42 x 10^6
	- [a] Gross margin from veld grazing on 80 667 ha by sheep plus cattle @R108·ha^{-1}	R	8.71 x 10^6	8.71 x 10^6
	- Gross margin for the downstream irrigation plus veld grazing strategy	R	11.02 x 10^6	10.13 x 10^6
	- [b] Gross margin on rain-water use for irrigation and grass $\left(\frac{GM_A \text{ or } GM_B}{0.537x80667x10^4}\right)$	R·m^{-3}	0.0254	0.0234
IRWH	- Maize produced on 80 667 ha at 1.7 t·ha^{-1}	t	137 134	-
	- Gross income @ R700·t^{-1} for maize	R	95.99 x 10^6	-
	- [c] Allocatable costs @ R1 000·ha^{-1}	R	80.67 x 10^6	-
	- Gross margin from 80 667 ha	R	15.32 x 10^6	-
	- Gross margin on rain water use for IRWH $\left(\frac{15.32x10^6}{0.537x80667x10^4}\right)$	R·m^{-3}	0.0354	-

[a] The procedures used to obtain these data are from Snyman (1998), with adjustments for current conditions by Snyman (2005), and Free State Department Agriculture Economist, H van Rensburg (2005). The data apply to commercial farmers.
[b] GM_A = Gross margin based on Scenario A, GM_B = Gross margin based on Scenario B.
[c] (Khundhlande et al., 2004)

(Hensley et al., 2000). Because of this, maize production using conventional tillage in the UMMRB is currently almost negligible. These facts eliminate the need to include maize production using conventional tillage as one of the options in Table 3.

The two strategies given in Table 3 are, firstly, veld-grass in the catchment and using the runoff for centre-pivot irrigation downstream; and secondly IRWH in the catchment.

The results in Table 3 show the expected total production under the two production strategies. The monetary benefit derived from these different strategies will be dealt with in the economic analysis (Table 4). The comparison of total maize production under the two production strategies shows that using rainfall where it falls within the catchment ('on-site') with the IRWH technique results in the production of six times more maize production than the downstream ('off-site') irrigation strategy. This information makes it quite clear that the 'on-site' use of rain-water as described constitutes the best catchment management decision. The large amount of water losses during storage and conveyance are probably the main reasons for the lower production of the irrigation option. It should also be noted that investment in the development of irrigation systems for a viable farming business is far from being accessible to small-scale farmers who are struggling to meet even their daily food requirements. The IRWH technique therefore offers an attractive option at this moment towards meeting household food security in the communal farming area. This, however, will require a concerted effort on the part of the Department of Agriculture (both national and provincial) and other stakeholders to promote the technique and to develop the skills of the small-scale farmers to make the system viable and sustainable.

Economic assessment of the two production strategies

A preliminary economic assessment of the two strategies is presented in Table 4. The combined irrigation plus veld-grazing strategy is shown to yield a combined gross margin of 0.0254 and 0.0234 R·m^{-3} of rainwater, for Scenarios A and B respectively. It is interesting to note that the contribution of the irrigation component to the gross margin of the combined strategy only amounts to 21% and 14% in the cases of Scenarios A and B respectively. The comparable far superior figure for the use of the IRWH technique to produce maize is 0.0354 R·m^{-3}. In monetary terms, the estimated IRWH advantage amounts to R4.3m.per annum and R5.2m. per annum for Scenarios A and B respectively. When expressed in terms of gross margin per ha, maize production using the IRWH technique is estimated at R190·ha^{-1}·yr^{1} using the figures presented in Table 4. For the 15 000 ha of communal land, this indicates an income of around R2.8m.per annum from areas where currently maize production is almost negligible and the people are struggling to meet daily food requirements.

The results in Table 4 provide economic support for the conclusions based on the data in Table 3. It is clear that it would be a wise catchment management decision to allow maize production using the IRWH technique to be developed in the UMMRB. It is of value to include here relevant information presented by Kundhlande et al. (2004) i.e., that among the communal farmers a family of five needs about 1t of maize per annum to supply their staple food. Therefore, the estimated maize production on the approximately 15 000 ha of the IRWH suitable land in the communal farming area within the UMMRB would be sufficient to supply the staple food for about 25 500 families or 127 000 people. This is a far larger number than is actually settled on the 15 000 ha, but less than the total population of the region if the towns of Botshabelo and Thaba Nchu are included.

Conclusions

The ultimate goal of a water resource policy in river basin management is to increase the beneficial utilization of the rain water falling in the catchment through reduction of non-beneficial losses and water pollution. In-field rain-water harvesting coupled with appropriate farming practices can contribute towards achieving this goal. The IRWH technique introduced to the small-scale communal farmers in the UMMRB is one such practice designed to increase crop yields under dry-land production compared to conventional tillage, and hence increase green water productivity.

The key data for the focal point of this study are presented in Tables 2, 3 and 4. They aim at providing the information needed for the relevant catchment management decision regarding wise use of rain water falling on the 80 667 ha of land in the UMMRB considered being suitable for the IRWH technique. The data clearly show that from all points of view, i.e. green water productivity, social considerations and economics, it would be a wise decision to allow the IRWH technique to be expanded in the UMMRB rather than suppress development to the benefit of downstream irrigation. However, the challenges faced by these farmers in the application of the IRWH technique are such that it could affect the expansion thereof, and should be addressed by the concerned governmental departments and non-governmental organizations operating in the area.

What may become a regulating factor in the future is the growing need for more water for municipal and industrial purposes in the ever growing Bloemfontein, Botshabelo and Thaba Nchu areas. This is an issue that needs to be addressed using very reliable information regarding the relative importance of saving water for future growing urban and industrial demand, vs. solving the current dire situation of small-scale farmers, who are struggling to meet their household food security in a more sustainable way. However, it should be emphasized that water loss reduction and control are considered to be parts of basin-wide integrated water resource management, which gives an essential role to institutions and policies in ensuring that upstream interventions are not made at the expense of downstream water users. These principles apply at all scales, from field to basin levels, but the associated options and practices require different approaches at different spatial scales. Therefore, there is a need to identify the types of policies and incentives that will work best in promoting adoption of new production techniques and cultural practices which increase water productivity at all levels.

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