ABSTRACT

The Karkheh River Basin (KRB) is the third largest and most productive river basin of Iran. The major agricultural issue of the KRB is low water use efficiencies. Farmers’ irrigation practices are aimed at maximizing crop production through excessive use of irrigation water resulting in huge water losses. As the opportunities for water resources development in the KRB are very limited, improving the productivity of existing water resources is the most attractive option to produce more food for the increasing population. This paper analyses water productivity of irrigated wheat and maize in the KRB. The results reveal that farmers having access to groundwater tend to apply higher irrigation amounts. Relatively higher crop yields in irrigated areas are also linked to higher nitrogen use, which might create serious problems of groundwater contamination in the future. Due to excessive use of groundwater and fertilizer, production costs have increased, resulting in low gross margins (farm incomes). The study suggests that an increase in charges for surface water use and removal of subsidies on electricity will discourage excessive use of water for agriculture. Furthermore, farmers should be trained to optimize irrigation water and fertilizer application in order to save scarce water resources and reduce production costs and increase farm returns. These steps are of great importance for ensuring sustainability of irrigated agriculture and to alleviate poverty in rural areas of the KRB.

KEY WORDS: Karkheh River Basin; Iran; water productivity; gross margins; groundwater; irrigated wheat; irrigated maize

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RÉSUMÉ

Le bassin de la rivière Karkheh (KRB) est le troisième des plus grands et productifs bassins fluviaux de l’Iran. La principale question agricole de KRB est la faible efficacité de l’eau. Les pratiques d’irrigation des agriculteurs visent à maximiser la production avec un usage excessif de l’irrigation conduisant à d’énormes pertes d’eau. Comme les possibilités de développement des ressources en eau dans KRB sont très limitées, l’amélioration de la productivité de l’eau est la meilleure option pour produire plus de nourriture pour la population croissante. Ce document analyse la productivité de l’eau pour l’irrigation du blé et du maïs dans KRB. Les résultats révèlent que les agriculteurs ayant accès à l’eau souterraine ont tendance à appliquer des quantités d’eau plus élevées. Les rendements plus élevés en zone irriguée sont également liées à une plus grande utilisation d’azote qui peut créer de graves problèmes de contamination des eaux souterraines à l’avenir. Avec un usage excessif des eaux souterraines et des engrais, les coûts de production ont augmenté, entrainant une diminution des marges brutes (revenu agricole). L’étude suggère qu’une augmentation des tarifs pour l’utilisation des eaux de surface et la suppression des subventions pour l’électricité vont décourager l’usage excessif de l’eau pour l’agriculture. En outre, les agriculteurs

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La productivité de l’eau pour l’irrigation du blé et du maïs dans le bassin de la rivière Karkheh en Iran.

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devraient être formés pour optimiser l’usage de l’eau d’irrigation et des engrais afin de sauvegarder les ressources en eau limitées, réduire les coûts de production et accroître le rendement agricole. Ces mesures sont essentielles pour assurer la durabilité de l’agriculture irriguée et lutter contre la pauvreté dans les zones rurales de KRB.

MOTS CLÉS: bassin de la rivière Karkheh; Iran; productivité de l’eau; marge brute; eau souterraine; blé irrigué; maïs irrigué

INTRODUCTION

Amongst global resources, water is emerging as the most critical and misused natural resource. It is an important input to agricultural production and an essential requirement for domestic, industrial and municipal activities. Increasing population and standards of living are contributing to a steep rise in demand for fresh water. The consequent wastage, over-exploitation, pollution and depletion of fresh water pose a serious threat to the food security of an increasing population. Recent studies indicate that one-third of the population of developing countries live in absolute water scarcity, in the sense that they will not have sufficient water resources to meet their agricultural, domestic, industrial and environmental requirements in the year 2025 (Seckler et al., 1998a, b). In semi- (arid) areas where opportunities for the development of new water resources are limited and costs are rising, increasing the productivity of existing water resources seems a realistic target. Improving agricultural water productivity is central for both economic and social development. Therefore there is every motivation to designate more efforts into increasing the productivity of water in agriculture to meet the future food demand of an increasing population (Sarwar and Bastiaanssen, 2001).

Irrigated agriculture has played an important role since the 1960s in feeding the growing world population and is expected to continue in the future as well (Cai and Rosegrant, 2003). However, water availability for irrigation in developing countries (now over 90% of water resources are used for irrigation) has had to be reduced due to increasing demand of water from non-agricultural sectors. The situation in the KRB is not much different from other parts of the world where about 93% of the total withdrawals are diverted to meet agricultural requirements. In the absence of sufficient surface water resources, groundwater use in the basin has increased manyfold over the last two decades. The future of irrigated agriculture, which produces more than 60% of total grain production, is threatened by low crop yields, low water use efficiencies and increasing salinity and waterlogging problems. Average water productivities of annual crops such as wheat and barley are 0.5 kg m$^{-3}$, which are far lower than 0.9 kg m$^{-3}$ for nearby Syria (Oweis et al., 1999).

The Karkheh River Basin (KRB) has traditionally been the central point of agricultural activities in Iran. Adequate water resources and favourable climatic conditions make it suitable for growing a wide range of crops. Increasing population pressure over the last three decades has resulted in over-exploitation and degradation of natural resources, making it one of the most vulnerable and poor areas of the country. The KRB has now become a water-short area and increasing incidences of drought have further compounded the problem. As a result, livelihoods of rural communities are at stake. Considering the present pace of deterioration, it is envisaged that situation will get worse in the near future.

In the KRB the possibility of increasing water resources is very limited. Therefore additional crop production will have to be achieved by increasing the productivity of the available water resources (Keshavarz et al., 2003). For this purpose, a better perception of the water-related interactions that occur across spatial and temporal scales, and within different locations in the same basin, is imperative. These analyses are essential for a better understanding of existing limitations to land and water productivity in different sub-basins of the KRB. This paper analyses the current status of land and water productivities of irrigated wheat and maize in five sub-basins of the KRB. Factors affecting land and water productivity are evaluated and means of improvement are suggested.

STUDY AREA

The Karkheh River Basin (KRB) is situated in the west of Iran and covers a surface area of about 51 000 km$^2$ (Figure 1), of which 55% is comprised of mountains and 45% of plains (Shahram et al., 2004). The climate of the
KRB is mainly semi-arid with large variations in the average annual precipitation between the southern and northern regions. In the southern region, average annual precipitation is about 150 mm, whereas in the northern region it can go up to 750 mm. About 75% of the rainfall falls in the first six months of the year (January–June) and the remaining 25% mainly falls in autumn (October–December), leaving the summer almost dry. Due to extremely high temperatures, about 65% of the rainfall is directly evaporated without any beneficial use. Evaporative demand of the KRB is very high. Class A pan evaporation in the basin ranges from 2000 to 3600 mm yr\(^{-1}\), of which 50% occurs just in the three summer months.

The water resources of the KRB comprise both surface water and groundwater. The volume of water generated by the average annual rainfall in the basin is 24.9 \(\times 10^9\) m\(^3\), of which 5.1 \(\times 10^9\) m\(^3\) is flood and surface water, 3.4 \(\times 10^9\) m\(^3\) infiltrates to groundwater and the remaining 16.4 \(\times 10^9\) m\(^3\) is lost directly to the atmosphere. The quality of river (surface) water is generally good, though it varies both seasonally and along the path downstream, reaching up to 3 dS m\(^{-1}\) near the final outlet. The Karkheh basin comprises five major sub-basins, i.e. the Gamasiab, Qarasu, Seymareh, Kashkan and south-Karkheh as shown in Figure 1. Basic characteristics of these five sub-basins are given in Table I.

Groundwater exploitation in the KRB was started as early as 1915 when the first well was dug in the basin (Shahram et al., 2004). However, during the last three decades, groundwater exploitation has taken a quantum jump

![Figure 1. Location of Karkheh River Basin with the boundaries of its five major sub-basins. This figure is available in colour online at www.interscience.wiley.com/journal/ird](http://www.interscience.wiley.com/journal/ird)

| Sub-basins       | Total area (km\(^2\)) | Irrigated area (ha) | Average annual rainfall (mm) | Groundwater table depth (m) |
|------------------|------------------------|---------------------|-----------------------------|-----------------------------|
| Gamasiab         | 11 500                 | 136 000             | 465                         | >15                         |
| Qarasu           | 5 350                  | 27 600              | 435                         | >10                         |
| Kashkan          | 8 960                  | 54 300              | 390                         | >10                         |
| Seymareh         | 16 400                 | 49 000              | 350                         | >10                         |
| South-Karkheh    | 8 590                  | 111 000             | 260                         | 1–3                         |

Table I. Basic characteristics of five sub-basins of the KRB
and currently groundwater accounts for nearly half of the urban and agricultural water supply in the KRB. Total exploitation of groundwater in the KRB is about 3856 million m³ yr⁻¹. This groundwater is exploited through 17 000 wells and 2677 springs (Jamab, 2006). About 87% of groundwater is used for agriculture, 12% for drinking purposes and about 1% is consumed by industry. In the upper parts of the KRB, groundwater quality is generally good for irrigation (EC ranges between 0.7 and 1.5 dS m⁻¹). However, in the lower parts of the KRB (south-Karkheh), groundwater quality is bad (EC ranges between 1 and 5 dS m⁻¹). This quality of groundwater together with shallow groundwater table depths poses a serious threat of waterlogging and secondary salinization in the irrigated areas of the lower parts of the basin. The risk of groundwater pollution through excessive leaching of nitrogen is very high in the lower KRB.

The total area of the KRB is 5.1 million ha (Mha), of which about 2.3 Mha are plain and mountainside and 2.8 Mha is mountain. According to 1994 estimates, about 894 000 ha are used for rainfed crops and 1.06 Mha suitable for irrigated crops. However, due to shortage of water, only 378 164 ha are currently irrigated every year. In irrigated areas, wheat, maize, rice, fodder, fruit and vegetables are common crops.

Despite the shortage of water, overuse of water in irrigation is very common. The present irrigation practices of farmers aim at providing maximum water for maximum crop production. The amount of water applied to each crop for irrigation has little relevance to actual crop water requirements. The depth of irrigation water mostly depends on the amount of water a farmer can capture. Therefore there is a general tendency to over-irrigate. At present, a big gap exists between water delivery from the main canals and water application in the field. Compared to the large investments for water resources development, little has been done to improve irrigation water use at farm level.

Water is delivered to old traditional irrigation canals and on-farm conveyances and the use of irrigation water is generally rudimentary and wasteful. The use of earth bunds, unlined canals and poor levelling combined with low water charges have resulted in very low levels of water conveyance and use efficiencies (30% as a national average) and caused the emergence of serious drainage problems. Another reason for low irrigation efficiencies is the use of traditional irrigation methods. Surface irrigation techniques are used on 98.75% of the area equipped for irrigation and 1.25% benefits from a pressurized irrigation system.

Two major agricultural production systems are present in the KRB. The rainfed system prevails mainly in the upper catchments and the fully irrigated areas are located mainly in the southern parts of the basin. The average annual rainfall in southern parts of the KRB can be as low as 150 mm. The soils are alluvial in nature formed originally by the floods of the river. These alluvial areas are relatively flat with low soil permeability. Due to poor natural drainage, these areas suffer from widespread soil salinity and waterlogging.

Over the past three decades, increasing access to water (mainly groundwater) has turned large rainfed areas into irrigated areas. Farm mechanization and increased use of subsidized fertilizer have resulted in a remarkable recovery of crop yields. Wheat yields in the upper KRB increased from 1500 kg ha⁻¹ in 1970 to over 5000 kg ha⁻¹ in 2004. Similarly, wheat yields in the lower KRB jumped from a mere 1000 kg ha⁻¹ to over 4000 kg ha⁻¹ during the same period. However, these yields are still lower than the other regions of Iran. Irrigation efficiencies are as low as 35% (Keshavarz et al., 2003). The amount of water applied to irrigate field crops is almost double what is actually required. As a result, productivity of water is very low, i.e. 0.5 kg m⁻³ for most of the field crops.

DATA COLLECTION AND METHODOLOGY

The analysis presented in this paper is based on the five-year (2001–05) data collected from the statistical department of the Ministry of Jihad-e-Agriculture and different research and development organizations working for the land and water development of the KRB. Data on actual yields and amounts of water applied for irrigation were collected through a comprehensive survey of the KRB during 2006. During this survey, 230 farmers from all over the basin were interviewed to gather information on yields, irrigation amounts applied, fertilizer use, causes of low yields and groundwater use in the basin. Due to farmers’ large areas located in the KRB, it was not possible to do field measurements to confirm survey results. However, in order to confirm the validity of secondary data and farmers’ claims, in situ measurements of crop yields and irrigation application rates were also done on selected farms in different parts of the basin. The measured data on crop yields and irrigation amounts were well within the
ranges described by farmers, which gives confidence in the survey results for further analysis. The analysis was done for wheat and maize as their coverage exceeds 60% of irrigated lands in the KRB.

The data collected from primary and secondary sources were analysed to calculate physical and economic water productivity of irrigated wheat and maize. Water productivity (WP) expresses the benefits or value derived from the use of water. Different indicators are used to describe physical water productivity. Most common are physical mass of production per unit of gross inflow, water depleted through evapotranspiration, or water available (Molden, 1997; Molden and Sakthivadivel, 1999). For classical analysis, water productivity is defined as yield per unit of water depleted. These water productivity values are usually higher than the values obtained by yield per unit of applied water. Since crop evapotranspiration depends on physiological processes, it does not show large variations in water productivity values. Therefore, the real challenge in water-scarce environments is to improve water productivity per unit of applied water because this is directly linked to on-farm water management improvements.

For this paper, physical water productivity (WPAW) is expressed in terms of crop yield per unit of irrigation water applied (kg m$^{-3}$). Economic productivity uses valuation techniques to derive the value of water, income derived from water use or benefits derived from water (Barker et al., 2003). Therefore, economic productivity is defined as gross value of production (WP_{GVP}) and gross margins (WP_{GM}) per unit of applied water (US$ m$^{-3}$). Gross margins are expressed in terms of GVP minus total cost of production.

RESULTS AND DISCUSSION

Crop yields

The average wheat yields for irrigated areas of five sub-basins of the KRB are given in Table II. The average yield for each sub-basin is calculated from the district level data whereas the basin average is based on sub-basin yield data. The average basin-wise irrigated wheat yield is 3547 kg ha$^{-1}$ with a standard deviation of 346, which is comparable to the countrywide average of 3577 kg ha$^{-1}$ (Ministry of Jihad-e-Agriculture (MoJA), 2005). The highest wheat yields in the Gamasiab and Qarasu sub-basins are related to higher fertilizer use and availability of groundwater for irrigation. Analysis of five-year data shows that average annual groundwater use for agriculture in the Gamasiab and Qarasu sub-basins was 191 and 161 million m$^3$, respectively. Groundwater use in south-Karkheh was only 52 million m$^3$, whereas Kashkan and Seymareh sub-basins were at the bottom with average annual use of only 30 and 22 million m$^3$, respectively. The use of groundwater is highest in the Qarasu sub-basin due to better accessibility. Despite lower irrigated area, the number of tubewells in Qarasu is 20% higher than the Gamasiab sub-basin. The relatively lower groundwater use in Kashkan and Seymareh sub-basins is associated with problems of installing tubewells in mountainous terrain. The lowest use of groundwater in south-Karkheh is linked to the poor quality of pumped water.

The considerably lower yields in the Kashkan sub-basin are related to poor soil fertility due to shallow soil depths and low fertilizer use. The relatively higher wheat yields in south-Karkheh are the result of increased access to surface water due to the newly constructed Karkheh dam and irrigation network developed in the area.

Table II. Wheat yields in irrigated areas of the five sub-basins of the KRB

| Sub-basins   | Wheat yields (kg ha$^{-1}$) |
|--------------|-----------------------------|
|              | 2001 | 2002 | 2003 | 2004 | 2005 | Average | SD |
| Gamasiab     | 3 552 | 3 757 | 3 982 | 4 395 | 4 124 | 3 962 | 326 |
| Qarasu       | 3 602 | 4 301 | 4 327 | 4 926 | 4 807 | 4 393 | 523 |
| Kashkan      | 2 250 | 3 097 | 2 465 | 2 708 | 2 289 | 2 562 | 349 |
| Seymareh     | 2 802 | 3 433 | 3 120 | 3 728 | 3 606 | 3 338 | 377 |
| South-Karkheh| 3 557 | 3 523 | 3 203 | 3 582 | 3 539 | 3 481 | 157 |
| Basin average| 3 153 | 3 622 | 3 419 | 3 868 | 3 673 | 3 547 | 346 |

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During the past few years, especially with the revolution in groundwater irrigation, maize production has taken the lead over other crops in the KRB. The maize area has reached 10% of the total irrigated area, with yields soaring to 9000 kg ha\(^{-1}\). The average maize yield at the basin level is 6675 kg ha\(^{-1}\) (SD = 938), ranging from 6000 kg ha\(^{-1}\) for the Kashkan sub-basin to almost 7500 kg ha\(^{-1}\) for the Gamasiab sub-basin (Table III). Like wheat, maize yields were also found to be higher in the Gamasiab and Qarasu sub-basins. The yields in the Kashkan and south-Karkheh sub-basins are also superior (6000 kg ha\(^{-1}\)), but fall short of the Gamasiab and Qarasu sub-basins by 1500 kg ha\(^{-1}\). Lower yields in south-Karkheh are related to prevailing soil salinity, whereas in Kashkan, poor soil fertility is the main cause of low maize yields.

**Applied water for irrigation**

In the KRB irrigation schedules vary a lot. The field measurements indicate that farmers having access to groundwater tend to apply more water for irrigation than those who are fully dependent on surface water. Farmers located in the upper part of the KRB use more groundwater as the quality of pumped water is suitable for irrigation. Farmers do not usually plan their irrigations in advance. Their decision mainly depends upon visual plant stress and accessibility to surface water and groundwater resources. Data collected in the field show large differences in the amounts of water applied for irrigation to wheat and maize in different sub-basins of the KRB (Table IV).

The average amount of water applied to wheat and maize is 3514 and 8284 m\(^3\) ha\(^{-1}\), respectively. The large gap between maximum and minimum values shows that farmers do not plan their irrigations according to crop water requirements. These findings are in agreement with the observations of Keshavarz et al. (2003). They have reported irrigation water applications of over 6000 m\(^3\) ha\(^{-1}\) for wheat and 10 000–13 000 m\(^3\) ha\(^{-1}\) for maize. These water application rates are also higher than the net irrigation requirements (crop water requirement – effective rainfall) recommended by the Ministry of Jihad-e-Agriculture. They have recommended 2600 m\(^3\) ha\(^{-1}\) for wheat

### Table III. Maize yields in irrigated areas of the five sub-basins of the KRB

| Sub-basins     | Maize yields (kg ha\(^{-1}\)) |
|---------------|-------------------------------|
|               | 2001 | 2002 | 2003 | 2004 | 2005 | Average | SD  |
| Gamasiab      | 8 221 | 7 607 | 7 313 | 7 559 | 6 672 | 7 474 | 560  |
| Qarasu        | 6 490 | 6 366 | 7 757 | 8 007 | 7 907 | 7 305 | 807  |
| Kashkan       | 3 934 | 5 246 | 8 212 | 7 672 | 4 876 | 5 988 | 1 857 |
| Seymareh      | 6 229 | 6 584 | 6 186 | 7 332 | 6 032 | 6 473 | 521  |
| South-Karkheh | 4 445 | 6 517 | 6 484 | 6 657 | 6 574 | 6 136 | 947  |
| Basin average | 5 864 | 6 464 | 7 190 | 7 445 | 6 412 | 6 675 | 938  |

### Table IV. Irrigation water applied to wheat and maize (m\(^3\) ha\(^{-1}\)) in the KRB

| Sub-basins     | Wheat |              |              | Maize |              |              |
|---------------|-------|--------------|--------------|-------|--------------|--------------|
|               | \(I_{\text{max}}\) | \(I_{\text{min}}\) | \(I_{\text{avg}}\) | \(I_{\text{max}}\) | \(I_{\text{min}}\) | \(I_{\text{avg}}\) |
| Gamasiab      | 7 776 | 1 980        | 4 628        | 13 230 | 6 800        | 9 752        |
| Qarasu        | 5 400 | 2 550        | 3 485        | 21 600 | 5 400        | 10 684       |
| Seymareh      | 5 950 | 1 620        | 3 172        | 8 500  | 4 320        | 6 239        |
| Kashkan       | 8 820 | 1 512        | 3 606        | 16 520 | 4 630        | 5 950        |
| South-Karkheh | 5 184 | 1 512        | 2 680        | 17 010 | 5 184        | 8 796        |
| Basin         | 6 626 | 1 834        | 3 514        | 15 372 | 5 267        | 8 284        |

\(I_{\text{max}}\): maximum water applied, \(I_{\text{min}}\): minimum water applied.
and 5900 m³ ha⁻¹ for maize, respectively (Ministry of Jihad-e-Agriculture, 1998). This is a clear demonstration of the fact that irrigation amounts applied by farmers have no relevance to actual crop water requirements. They usually tend to maximize their crop yields through excessive irrigation. However, in most cases irrigation water is applied at less water-sensitive stages of the growth cycle, causing significant losses through evaporation and deep percolation thereby reducing the efficiency of water use.

The survey data were also used to develop the relationship between irrigation water applied and yields for wheat and maize, and the results are presented in Figure 2. The correlation between crop yields and irrigation water applied is not straightforward, as it is often assumed by farmers that crop yield increases with increase in irrigation water applied. The $r^2$-squared values for the relation between yield and irrigation water applied are low for both crops. The difference is more pronounced for maize than wheat. This shows that there is a great need for farmers to shift their thinking from maximizing crop production through excessive water use to optimizing crop production with minimum irrigation supplies.

**Water productivity**

Table V gives physical and economic water productivity for wheat and maize in the KRB. The basin level $W_{PAW}$ of wheat is found to be 1.0 kg m⁻³, ranging between 0.71 kg m⁻³ for Kashkan to 1.30 kg m⁻³ for south-Karkheh. The highest $W_{PAW}$ in south-Karkheh can be ascribed to higher yields with limited water supply conditions. Lower $W_{PAW}$ for Kashkan is mainly related to higher water application and relatively lower wheat yields. Except for south-Karkheh, the calculated $W_{PAW}$ for wheat is lower than those observed in other regions of Iran. For similar climatic conditions, Afshar (2004) has reported $W_{PAW}$ values up to 1.32 kg m⁻³ for irrigated wheat in Mashad.

![Figure 2. Relationship between yield and irrigation water applied for wheat and maize](image-url)
### Table V. Physical and economic productivity of water for irrigated areas of the KRB

| Indicators                  | Gamsiab Wheat | Gamsiab Maize | Qarasu Wheat | Qarasu Maize | Seymareh Wheat | Seymareh Maize | Kashkan Wheat | Kashkan Maize | South-Karkheh Wheat | South-Karkheh Maize | Basin average Wheat | Basin average Maize |
|-----------------------------|---------------|---------------|--------------|--------------|----------------|----------------|----------------|---------------|---------------------|---------------------|---------------------|---------------------|
| Yields (kg ha\(^{-1}\))     | 3 962         | 7 474         | 4 393        | 7 305        | 3 338          | 6 473          | 2 562          | 5 988         | 3 481                | 6 136                | 3 547                | 6 675                |
| AW (m\(^3\) ha\(^{-1}\))   | 4 628         | 9 752         | 3 485        | 10 684       | 3 172          | 6 239          | 3 606          | 5 950         | 2 680                | 8 796                | 3 514                | 8 284                |
| Cost of production (US$ ha\(^{-1}\)) | 252         | 434          | 174          | 301          | 173            | 297            | 178            | 313          | 176                | 315                | 191                | 331                |
| GVP (US$ ha\(^{-1}\))       | 880           | 1 270         | 976          | 1 241        | 742            | 1 100          | 570            | 1 018        | 744                 | 1 043               | 788                 | 1 121               |
| GM (US$ ha\(^{-1}\))        | 628           | 836          | 802          | 940          | 569            | 803            | 392            | 705          | 568                 | 728                 | 597                 | 790                 |
| WP\(_{\text{AW}}\) (kg m\(^{-3}\)) | 0.86         | 0.77         | 1.26         | 0.68         | 1.05           | 1.03           | 0.71           | 1.00         | 1.30                | 0.70                | 1.00                | 0.80                |
| WP\(_{\text{GVP}}\) (US$ m\(^{-3}\)) | 0.19         | 0.13         | 0.28         | 0.11         | 0.23           | 0.18           | 0.16           | 0.17         | 0.21                | 0.12                | 0.22                | 0.13                |
| WP\(_{\text{GM}}\) (US$ m\(^{-3}\)) | 0.14         | 0.08         | 0.23         | 0.09         | 0.18           | 0.13           | 0.11           | 0.12         | 0.28                | 0.08                | 0.17                | 0.14                |
region of Iran and Oweis and Hachum (2001) have reported WP_{AW} of 0.93 kg m^{-3} with average yields going up to 5800 kg m^{-3} for Syria. This clearly shows that there is a good scope for improvement in water management to increase land and water productivity of different sub-basins in the KRB.

The average WP_{AW} for maize (0.80 kg m^{-3}) is found to be lower than wheat and other similar regions of Iran. Afshar (2004) has also reported WP_{AW} values of up to 1.0 kg m^{-3} for irrigated maize in the Mashad region of Iran. The average maize yields in the upper and lower KRB are 6700 t ha^{-1}, whereas individual farmers in Gamasiab are getting as high as 8000 kg ha^{-1}. These higher yields of maize are linked to excessive use of fertilizer and farm mechanization. The average fertilizer application rate for maize in the upper KRB is 300 kg N ha^{-1}, whereas for the lower KRB it is 170 kg N ha^{-1}. These substantially higher nitrogen application rates are the result of a government subsidy provided on fertilizers. Farmers apply these higher nitrogen rates to get substantive yields to make agriculture profitable. The WP_{AW} for maize is also lower than WP_{AW} values in Syria (1.2–1.5 kg m^{-3}) under similar environmental conditions (Zhang and Oweis, 1999). The major reason for lower WP_{AW} in the KRB is the higher amount of irrigation water applied as the average crop yields are comparable to other regions of Iran.

In water-limiting environments such as the KRB, the main objective of irrigated agriculture is to maximize the returns per unit of water and not per unit of land. In these environments, higher water productivity is usually linked with higher crop yields. However, this parallel relationship is not valid under all conditions (Zwart and Bastiaanssen, 2004). After attaining a certain higher level of yields, incremental yield increases require much more water, resulting in a significant reduction in efficiency of water use.

Figure 3 shows the relationship between yield and water productivity for wheat and maize in the KRB. This curvilinear relationship is stronger for maize than wheat. It is obvious that maximum water productivities for wheat and maize are achieved at yield levels of about 5000 and 7000 kg ha^{-1}, respectively. After this yield level, water productivities of both crops started to reduce, mainly because the amount of water needed to produce yields higher

![Figure 3. Relationship between crop water productivity and crop yield for wheat and maize. This figure is available in colour online at www.interscience.wiley.com/journal/ird](http://www.interscience.wiley.com/journal/ird)
than 5000 and 7000 kg ha\(^{-1}\) are much more than the amount of water required at lower yield levels. It is clear that in the water-scarce environment of the KRB, it would be more appropriate to optimize crop yields using less water rather than maximizing yields with excessive amounts of water.

Figure 3 also shows that higher water productivity values are usually obtained at less than maximum yields per unit land. Therefore these concepts make more sense in situations where water, and not land, is a limiting factor or where water shortages restrict irrigation of available lands. If the saved water resources are allocated to other cropped areas, the total production and productivity of applied water will be increased. However, in such conditions, farmers need to be guided on when and how much water should be applied in order to avoid unwanted water stress on plants.

Afshar (2004) found, for different locations in Iran, water productivity values of 1.5 and 1.3 kg m\(^{-3}\) against water applications of 3000 and 6000 m\(^3\) ha\(^{-1}\) for wheat and maize, respectively. He also noted that water productivity was considerably decreased when applied water exceeds 3000 and 6000 m\(^3\) ha\(^{-1}\) for wheat and maize, respectively. Hussain et al. (2003) also reported a wheat yield of 4500 and 4200 kg ha\(^{-1}\) against irrigation water application of 3050 and 3700 m\(^3\) ha\(^{-1}\) for Bhakra (India) and Punjab (Pakistan), respectively. The average annual rainfall at both locations is between 400 and 500 mm, which is comparable with average annual rainfall for the upper and middle parts of the KRB (i.e. 450 mm). Sarwar and Perry (2002) also reported increased water productivity under deficit irrigation conditions of Punjab, Pakistan. The corresponding water productivity values were 1.47 and 1.13 kg m\(^{-3}\), respectively. Even though production depends on conditions of the environment, the market, and the soil and water conditions are not equal across sites, there appears to be a considerable scope for improving productivity of water.

**Economic productivity**

For the calculations of economic productivity, gross value of production (GVP) and net gross margins (GM) in US$ per hectare were calculated using crop yields and prices of wheat and maize. Productivity of land shows the same pattern as of yields. The GVP for irrigated wheat is US$788, ranging from US$570 for Kashkan to US$976 for the Qarasu sub-basin. These differences are mainly related to yield differences in different sub-basins as the prices of wheat are fixed in the whole basin. The basin-level GVP for maize stands at US$1120, ranging from US$1018 for Kashkan to US$1270 for Gamasiab. The average basin-level GVP for maize is about 40% higher than average GVP for wheat. Higher GVP for maize corresponds to higher yields as per unit price for wheat is higher than maize. The variations in GVP values within sub-basins are relatively lower as compared to wheat.

The average production cost for wheat in Gamasiab is US$245 ha\(^{-1}\). The main contribution to this total comes from planting costs (US$60 ha\(^{-1}\)), followed by fertilizer and water charges (US$125 ha\(^{-1}\)) and harvesting costs (US$60 ha\(^{-1}\)). The higher production costs for maize are due to increased planting costs, water (mainly groundwater) charges and harvesting costs. In the upper and lower parts of Karkheh, most of the field operations such as planting, harvesting and weeding are done by modern farm machinery because field sizes are relatively large and manual operations are not economically feasible. The increasing use of machinery has helped to improve crop yields.

The gross margins (GM) are higher for maize than wheat. This is probably the reason why the maize cultivated area is increasing over time. The basin-level GM for maize is US$790 as compared to US$597 for wheat. Although average maize yields in Gamasiab are higher than Qarasu, gross margins are 12% higher for Qarasu. It is due to higher production costs in Gamasiab. The major contributors are groundwater pumping and fertilizer costs. It is evident from Table V that salinity has a pronounced effect on the productivity of land. In non-saline areas of the upper KRB, wheat yields are almost double those of the saline parts of the basin (south KRB).

Maximum crop water productivity often does not coincide with farmers’ interests as their objective is to maximize land productivity or economic profitability. Therefore attaining higher yields with increased water productivity is only economical when the increased gains in crop yields are not offset by increased input costs (Oweis et al., 1998). Figure 4 shows a comparison of WP\(_{GM}\) for wheat and maize in different sub-basins. WP\(_{GM}\) values for wheat are generally higher in all sub-basins. However, at the basin level, WP\(_{GM}\) values for wheat and maize are comparable. This is because of lower GVP and GM values for maize as a result of higher production costs. This stressed the need for farmers to optimize their maize yields through economical use of fertilizer and...
scarce water resources. This will not only increase their profitability but will also reduce groundwater pollution caused by heavy nitrogen leaching as a result of excessive fertilizer use. At present, these problems are not very evident in the upper parts of the KRB due to deeper groundwater tables, but continuation of these practices will have serious consequences in the future. Such measures are indispensable to ensure long-term sustainability of irrigated agriculture in this basin.

CONCLUSIONS AND RECOMMENDATIONS

The analysis presented in this paper clearly shows that there are considerable differences in crop yields and productivity of water for irrigated areas of the five sub-basins of the KRB. The results also suggest that in addition to water availability, location-specific factors such as soil fertility, fertilizer use and access to farm machinery are major contributing factors to crop yields and water productivity differences across the basin.

The most dominant factor for higher land productivity has been the increasing use of fertilizer and irrigation water. Individual farmers are more interested in increasing their land productivity and farm incomes and are less bothered by decreasing water productivity. This is probably due to the low cost of surface water in the KRB. Subsidized electricity for agricultural tubewells has also made groundwater use very economic. Therefore, increasing surface water charges and limiting groundwater pumping by removing subsidies on electricity could be potential options for restricting excessive water use for agriculture.

Farmers in the KRB are found to be ignorant of actual crop water requirements and tend to over-irrigate their lands. As plants are constrained in their capacity to extract more water than the atmospheric demand, extra water is lost as deep percolation to groundwater. Therefore, farmers need to be educated about the actual irrigation requirements for different crops. By practising improved irrigation schedules, deep percolation losses can be significantly reduced. This is especially needed in south-Karkheh where the groundwater is shallow and saline and any water lost through deep percolation cannot be reused.

Improved irrigation techniques will reduce the groundwater significantly, which will reduce the production costs and increase net farm income of farmers. The saved water can be used to bring more area under cultivation. As mentioned earlier, out of 1.06 million ha potential irrigated area, only 378 000 ha are currently being cultivated due to shortage of water. Therefore saving irrigation water would be of great importance for increasing the irrigated area and improving agricultural production in the country.

Irrigation dominates water use in the KRB and is expected to continue as a major user of both surface water and groundwater resources. Therefore, in order to increase sustainability of irrigated agriculture, the overall strategy should be to make better use of existing water resources. The irrigation water requirements for different crops under different agro-climatic zones of the KRB need to be calculated and disseminated. This will not only help in saving precious water resources but will also increase profitability of farmers. To enhance crop yields, farmers also need to
be made aware of improved crop varieties, application of appropriate rates of fertilizers and other advanced agronomic practices.

NOTES

1 The average fertilizer application rate for maize in the upper KRB is 300 kg N ha\(^{-1}\) whereas for the lower KRB this value is 170 kg N ha\(^{-1}\). These substantially higher nitrogen application rates are the result of government subsidy provided on fertilizers. Farmers claim that without such higher nitrogen application they cannot get substantive yields and their agriculture is not profitable. The nitrogen application rate for wheat and barley is 130–135 kg N ha\(^{-1}\). Within the KRB, higher nitrogen application is practised in Gamasiab, Qarasu and south-Karkheh mainly due to availability of irrigation water. For rainfed wheat and barley, nitrogen application rate is 50–60 kg N ha\(^{-1}\).

2 Wheat price in KRB is taken as 2000 rials per kg (US$0.22) whereas maize price is 1500 rials kg\(^{-1}\) (US$0.16). These are the prices at which government buys wheat and barley from farmers at the farm gate. Government sells the wheat flour back to the people at the subsidized rate of about 1500 rials kg\(^{-1}\) (US$0.17). Maize price is 1500 rials kg\(^{-1}\) (US$0.17), whereas chickpea price is taken as 6500 rials kg\(^{-1}\) (US$0.72) for the calculations of gross value product (GVP).

3 Increased production costs in Gamasiab are due to higher middle-stage expenses and harvesting costs. Middle-stage expenses include fertilizer costs, irrigation water costs and crop protection costs. Due to increased groundwater use in Gamasiab, irrigation costs are high. The average middle-stage costs for Gamasiab are about US$125 ha\(^{-1}\) as compared to US$50 for other sub-basins of the KRB. The harvesting costs in Gamasiab are US$60 ha\(^{-1}\) as compared to US$40 ha\(^{-1}\) for other parts of the KRB. In south-Karkheh harvesting charges by combines are based on an hourly basis, whereas in Gamasiab harvesting charges are based on a percentage of total yields obtained per ha. This is due to higher yields in Gamasiab.

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