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Supplemental irrigation potential and impact on downstream flow of Karkheh River Basin of Iran

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Abstract

Supplemental irrigation of rainfed winter crops improves and stabilizes crop yield and water productivity. Although yield increases by supplemental irrigation are well established at the field level, its potential extent and impact on water resources at the basin level are less researched. This work presents a GIS-based methodology for identifying areas that are potentially suitable for supplemental irrigation and a computer routine for allocating stream flow for supplemental irrigation in different subbasins. A case study is presented for the 42 908 km^2 upper Karkheh River Basin (KRB) in Iran, which has 15 840 km^2 of rainfed crop areas. Rainfed crop areas within 1 km from the streams, with slope classes 0–5 %, 0–8 %, 0–12 % and 0–20 %, were assumed to be suitable for supplemental irrigation. Four stream flow conditions (normal, normal with environmental flow requirements, drought and drought with environmental flow) were considered for the allocation of water resources. Thirty-seven percent (5801 km^2) of the rainfed croplands had slopes less than 5 %. Sixty-one percent (3559 km^2) of this land was suitable for supplemental irrigation, but only 22 % (1278 km^2) could be served with irrigation in both fall (75 mm) and spring (100 mm), under normal flow conditions. If irrigation would be allocated to all suitable land with slopes up to 20 %, 2057 km^2 could be irrigated. This would reduce the average annual outflow of the upper KRB by 9 %. If environmental flow requirements are considered, a maximum (0–20 % slopes) of 1444 km^2 could receive supplemental irrigation. Under drought conditions a maximum of 1013 km^2 could be irrigated, while the outflow would again be reduced by 9 %. Thus, the withdrawal of steam flow for supplemental irrigation has relatively little effect on the outflow of the upper KRB. However, if the main policy goal would be to improve rainfed areas throughout the upper KRB, options for storing surface water need to be developed.

1 Introduction

To achieve the world's growing needs for food, a better allocation of water resources for irrigation is needed. Supplemental irrigation is the application of a limited amount of water to essentially rainfed crops during dry spells to alleviate moisture stress, thus improving and stabilizing yields (Oweis and Hachum, 2006). Supplemental irrigation is recommended for field crops in areas with an annual rainfall range of 300–600 mm. The goal of supplemental irrigation is not to maximize yield per unit area but to optimize water productivity (benefit per unit water). Results of research experiments have shown substantial increases in crop yields and water productivity in response to the application of relatively small amounts of supplemental irrigation (Ghahraman and Spaskhah, 1997; Oweis et al., 1998, 2000; Fox and Rockström, 2003; Tavakoli and Oweis, 2004; Oweis and Hachum, 2006). At the farm level, supplemental irrigation increases yields, water productivity, and stability of crop production under different climatic conditions. These increases depend on site-specific environmental factors and management practices such as rainfall amount and distribution (especially at sowing date and heading-flowering stage), soil characteristics, crop cultivar, agronomic practices including fertilizer (amount, source and timing), machinery and control of weeds, pests and disease.

The Karkheh River Basin (KRB) in Western Iran served as a benchmark basin for the Challenge Program on Water and Food of the Consultative Group on International Agricultural Research (CGIAR) and a number of hydrological assessments have been recently published (e.g. Muthuwatta et al., 2010; Masih et al., 2011). Most of the agricultural area in the upper KRB is rainfed. Annual precipitation in the upper catchments of the KRB ranges from 350 to 500 mm and yields of the dominant wheat crop are low. Iran's agricultural strategy identifies water productivity improvement as a top priority. Supplemental irrigation has been recommended as an important practice for increasing crop and water productivity in these rainfed areas of the upper KRB, which comprise important suitable rainfed zones of Iran (Keshavarz and Sadeghzadeh, 2000; Tavakoli et al., 2008, 2010).

The effects of supplemental irrigation on the yield of rainfed bread wheat (*Triticum aestivum* L.) was investigated under different scenarios in on-farm experiments conducted during the 2005-08 cropping seasons at multiple farms in two benchmark watersheds in the upper KRB. The treatments included two main management strategies (traditional and advanced management) and four levels of irrigation: (i) rainfed, (ii) a single irrigation of about 50 mm at planting, (iii) a single irrigation of 75 mm in spring and (iv) 50 mm at planting and 75 mm in spring. The results showed that a single irrigation application at sowing or spring time (during heading to flowering stage) increased total water productivity of wheat from 0.35 $kg\,m^{-3}$ to an average of 0.57 to 0.63 $kg\,m^{-3}$ over the three growing seasons. The average irrigation water productivity of wheat, which quantifies the yield increase (irrigated minus rainfed yield) due to irrigation, reached a range of 2.15–3.26 $kg\,m^{-3}$. The application of the supplemental irrigation at critical stages, deep root expansion, increased green canopy cover and its influence on evaporation control were main reasons for the effectiveness of supplemental irrigation. These results confirmed the potential of a single irrigation, either with early or normal planting, as an effective scheme to enhance productivity (Tavakoli et al., 2008, 2010).

A methodology that uses Geographic Information Systems (GIS) tools to identify potential areas for the introduction of supplemental irrigation has been developed by De Pauw et al. (2008). The method was based on the assumption that the irrigation water (from either surface or groundwater) used to fully irrigate summer crops in existing irrigated schemes could instead be used in winter and spring for supplemental irrigation of winter crops. Since water requirements for supplemental irrigation are a fraction of that for full irrigation, the areas that could be irrigated in winter (wet and cold) are much larger than the areas currently used for full irrigation in summer (dry and hot). The method used a combination of a simple model to calculate the additional rainfed area that can be partially irrigated by the possible water savings, made by the shift from fully-irrigated spring/summer crops to supplemental-irrigated winter/spring crops, with a water allocation procedure for the surrounding rainfed areas based on suitability criteria (De Pauw et al., 2008). A drawback of this method is that it implicitly assumes

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that current irrigation water withdrawals are sustainable, while its implementation would also require that farmers abandon or reduce summer cropping.

Allocation of limited water resources, environmental quality and policies for sustainable water use are issues of increasing concern. The challenge is to determine the amount of water, and its quality, that should be allocated for the maintenance of the ecosystems through an "environmental flow allocation" and the water that can be allocated for agriculture, industry, and domestic services (Ramsar Convention Secretariat, 2007). Methods for estimating environmental flow requirements (EFR) include: hydrological methods, hydraulic rating, habitat simulation and holistic methods (Mazvimavi et al., 2007). More than 30 criteria for single river EFR have been developed and used worldwide (Hughes and Hannart, 2003; Mazvimavi et al., 2007; Ramsar Convention Secretariat, 2007; Smakhtin, 2001; Smakhtin et al., 2006). However, a lack of hydro-ecological studies often limits the choice of an EFR method.

The objective of the present study is to develop a method for identifying potential areas for supplemental irrigation of rainfed cropland and to assess the consequences of supplemental irrigation on downstream flow under different flow conditions. The methodology was applied to the 43 000-km^2 upper KRB in Iran.

2 Methods

The analysis involved the following five steps: (1) processing of the Digital Elevation Model (DEM), obtained from the 90-m resolution, Shuttle Radar Topography Mission (SRTM); (2) selection of a set of stream flow gages spanning the appropriate period of record and delineation of the watersheds of the selected gauges; (3) determination of the supplemental irrigation water needs and the environmental flow requirements for each subbasin; (4) identification of the areas suitable for supplemental irrigation; and (5) dynamic allocation of water to areas suitable for supplemental irrigation per subbasin and downstream routing. Step 5 was repeated for four different flow scenarios

and two irrigation options and provides the flow reduction to the Karkheh dam. Steps 2 to 5 are described in more detail below.

2.1 Study area

The Karkheh River Basin (KRB) is located in the southwest of Iran, between 30°58′ to 34°56′ N latitude and 46°06′ to 49°10′ E longitude. The area is about 50 700 km^2, with considerable variation in elevation, from a minimum of 3 m a.s.l. in the south (Dasht Azadeghan) to a maximum of 3645 m in the Karin Mountains in the north. The population of the area is around 4 million and is concentrated in the main cities and towns of Kermanshah, Khoramabad, Malayer, Songor, Kamyaran, Nahavand and Sosangerd; otherwise the Karkheh River Basin is rural. The area upstream of the Karkheh dam, referred to as upper KRB, covers 42 908 km^2. The main Karkheh river has a length of about 900 km. The climate of the basin is semi-arid to arid. Most of the agricultural area in the upper KRB is rainfed and a large part of the region's agricultural livelihoods is based on dryland farming systems.

2.2 Selection of flow gauging stations

To cover both dry and wet periods a 30-yr period was used for the flow analysis. Flow gauge stations operating in KRB during the 1975–2004 period with at least 10 yr data were selected, yielding a set of 53 stations. Key attributes available for each station record are latitude, longitude, starting year and ending year. The 53 subbasins were delineated with the help of the DEM. Mean monthly flows were computed for the 30-yr period. Missing monthly data were filled in using linear regression relations and the normal ratio method (ASCE, 1996). A maximum coefficient of determination (R^2), a statistically significant model (p-value 0.05), and availability of the corresponding data were the criteria for selecting suitable nearby stations from which to obtain the missing data. A map of Upper KRB with the 53 watersheds is presented in Fig. 1.

2.3 Water resource requirements

Water requirements include: existing needs (irrigation, industry, domestic), new supplemental irrigation requirements, and environmental flow requirements (EFR). At each gauge station flows in excess of the domestic, industrial and irrigation uses are recorded. Thus, the recorded stream flow data assumes all existing needs are satisfied.

The supplemental irrigation requirements were taken from a field study undertaken in KRB (Tavakoli et al., 2008, 2010), but with consideration of conveyance efficiency. The following strategies were considered: (i) applying a single irrigation of 100 mm in autumn; (ii) applying two irrigations of 75 mm each in the spring. Wheat is planted in October and harvested in early July. Autumn irrigations are applied in October and spring irrigations in June. Temperatures in the three lowest subbasins before the dam (22, 33 and 39) are higher than those in the remainder of the basin, and here crops are planted later and harvested earlier. In these basins irrigations are applied in November and April. The monthly irrigation water requirements for each sub-basin are calculated based on the mapped suitable areas, as explained below.

Discharge data variation and the wet and dry thresholds of surveyed sub-basins and base flow in sub-basins determine the water available for allocation. In this research, 15 % of the mean annual runoff (MAR) of each subbasin was used as an EFR. By subtracting the EFRs from the monthly flow data, available water for allocation to supplemental irrigation areas of all sub-basins could be determined.

2.4 Areas suitable for supplemental irrigation

All rainfed crop areas with less than 20 % slope were considered potentially suitable for supplemental irrigation. The rainfed crop areas were taken from the land use/land cover map of Iran (FRWO, 1998). The map was overlayed with the slope map derived from the DEM, to identify four different slope classes: 0–5 %, 5–8 %, 8–12 %, and 12–20 %. These slope classes determine the suitability of land for different types of irrigation and could be used to set different priorities for irrigation expansion. The slopes used for

different irrigation methods are: surface (less than 5 %), sprinkler (0–8 %), and trickle (0–12 %). Ideally, slopes above 12 % should neither be cultivated with field crops nor irrigated, because it leaves the land vulnerable to erosion.

River surface flow was assumed to be the sole source of water for irrigation. Potential rainfed areas for supplemental irrigation were considered within buffers of 1000 m around the streams. The buffer is based on expert knowledge of the maximum distance that is feasible for conveying water away from the water source. To determine areas suitable for supplemental irrigation in each subbasin, the stream buffer area map is overlayed on that of the rainfed slope classes of the 53 subbasins, from which the so-called iso-potential map for supplemental irrigation is derived (Fig. 1).

2.5 Water allocation

A Fortran program was developed to dynamically allocate the stream flow to the areas suitable for supplemental irrigation. To ensure that sufficient water remains for all current water allocations, first the available stream flow in each subbasin is computed. Starting from downstream, the available flow of each subbasin is computed by subtracting the inflow from upstream basins from the outflow of the subbasin. If the outflow from a subbasin is less than the sum of the inflows, the flow deficit is distributed among its inflowing upstream subbasins, relative to their flow. Thus the available flow of upstream subbasins is the outflow minus the inflows and minus an equitable share of any deficit of the downstream subbasin. Then starting from the upstream subbasins, the available water is allocated to the supplemental irrigation areas, and any remaining water is routed downstream.

Four different flow scenarios were applied: (i) the 30-yr mean flow, referred to as normal; (ii) normal with EFR; (iii) drought flow conditions; (iv) drought conditions with EFR. The drought flows of the subbasins were defined as the flows with an 80 % probability of exceedance. For each flow scenario, four slope classes were used: 0–5 %, 0–8 %, 0–12 % and 0–20 %. Finally, two irrigation options were simulated: (i) supplemental irrigation in both spring and fall and (ii) supplemental irrigation in either fall or

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spring or both, depending on water availability. The first option is more restrictive, because it would consider to irrigate only the areas that have sufficient stream flow in both seasons. Thus, the program is used to compute actual supplemental irrigation areas in Upper KRB sub-basins for different land suitability classes, flow scenarios, and irrigation development options.

By applying the computer program, actual areas suitable for the development of supplemental irrigation and the flows that can be allocated for irrigation are calculated along the river. The impacts of the scenarios on stream flow are evaluated for each sub-basin and, subsequently, for the whole basin. Finally, the effect of the four scenarios on the outflow to the Karkheh dam is compared.

3 Results and discussion

The rainfed crop areas cover 15 840 km^2 of the total 42 908-km^2 area of upper KRB. More than one third (37 %) of the rainfed crop land has slopes up to 5 %, while 50 % of the rainfed areas have slopes up to 8 %. The higher slope classes cover 13 % (8–12 % slope) and 16 % (12–20 % slope) of the rainfed areas, whereas 21 % are not suitable for cultivation.

Sixty-one percent (3559 km^2) of the rainfed crop areas with slopes up to 5 % are suitable for supplemental irrigation due to their location within 1000-m buffer distance of the streams. This is 22 % of the total rainfed crop area. If all rainfed croplands with slopes up to 20 % are considered, 46 % (7361 km^2) of the total rainfed crop area is suitable for supplemental irrigation. The location of these areas is shown in Fig. 1. These numbers are in the same range as those of Masih et al. (2011), who found, without specifying the exact criteria used, that 33 % (4680 km^2) of the 14 020-km^2 rainfed crop area in upper KRB could be potentially converted to irrigated agriculture.

Figure 2 presents the upper Karkheh River Basin rainfed crop areas for the four slope classes (0–5 %, 0–8 %, 0–12 %, 0–20 %), the areas suitable for supplemental irrigation (within 1-km buffer from the streams) and the suitable areas that could receive

supplemental irrigation under the four flow scenarios. The figure clearly shows that the stream flow is sufficient to irrigate only a fraction of the suitable rainfed areas within 1-km from the streams. For application of irrigation in both fall and spring (Fig. 2a) under Normal flow, 36 % (1278 km^2) of the suitable rainfed land on 0–5 % slopes can be irrigated or 28 % (2057 km^2) of the suitable rainfed land on 0–20 % slopes.

The 30-yr mean flows (Normal) at the Karkheh dam are lowest between August to October (54–57 m^3 s^{-1}) and highest in March (363 m^3 s^{-1}), April (421 m^3 s^{-1}) and May (284 m^3 s^{-1}). Because of the scarcity of water in autumn, the more restrictive irrigation option, which requires water for both fall and spring irrigation (Fig. 2a), covers about half of the area that will be irrigated under the less restrictive option, which applies either fall or spring irrigation (Fig. 2b). Under drought conditions, outflows to the dam average 42 m^3 s^{-1} in October and 126 m^3 s^{-1} in May. But there is little water in the upstream areas of upper KRB, which are most suitable for supplemental irrigation, and the difference between the two irrigation options remains small.

Figure 3 shows the average annual stream flow to Karkheh dam before and after the application of supplemental irrigation, for the four flow scenarios, four slope classes and two irrigation options. Note that without supplemental irrigation the outflows with and without EFR remain the same. For irrigation in fall and spring (Fig. 3a) and Normal flow conditions, the average annual flow (177 m^3 s^{-1}) is reduced by 9 %, if all slope classes (0–20 %) are irrigated. If EFR are considered the flow reduction becomes 6 %. The results indicated that the EFR of 15 % of the mean annual flow throughout the basin may be a suitable criterion for reducing environmental impact of irrigation water withdrawal. Under drought conditions the average annual flow to the dam is 90 m^3 s^{-1} and the relative flow reductions are similar.

For the less restrictive irrigation option (Fig. 3b) the reductions of downstream flows for the irrigation of all slope classes were 15 % for Normal flow, 13 % for Normal Flow with EFR, 9 % for drought conditions and 6 % for drought conditions with EFR. Similar results were found by Masih et al. (2011), who used the Soil Water Assessment Tool

(SWAT) to analyse the impact of the conversion of rainfed crops to fully irrigated crops. They found a reduction of 10 % in the average annual stream flow of upper KRB.

The results of the analysis indicate that implementation of supplemental irrigation in the rainfed areas will not reduce the average annual flow to the Karkheh reservoir significantly. Furthermore, the reservoir storage will also reduce the impact of the seasonal withdrawals. At the same time, supplemental irrigation is expected to provide considerable benefits for yield and water productivity in the upper KRB.

Figure 4 shows the supplemental irrigation areas of the 53 sub-basins for the four flow scenarios and three slope classes. These figures clearly show that in the upstream subbasins water is the limiting factor, whereas in the downstream areas good quality land is a limiting factor. Under the two normal flow scenarios, in the upstream subbasins, all available water is used to irrigate rainfed lands with slopes less than 5 %. But for the downstream subbasins, the irrigated area keeps on increasing if we move from the first slope class (0–5 %) to the third (0–12 %) and fourth slope class (0–20 %).

The maps for the drought scenarios also provide an important message. In drought years, when the rainfed crops will be water-stressed, no stream flow is available for supplemental irrigation in the upstream subbasins. However, even under the drought scenario a total of $2.7 \times 10^9\,m^3\,yr^{-1}$ will flow to the dam. Thus, to irrigate a larger share of the rainfed areas, water need to be stored in the upstream areas in small and medium sized dams and perhaps also through artificial groundwater recharge. Water should be captured during the wet winter and early spring months for subsequent use later in spring.

4 Conclusions

A methodology was developed that allows the allocation of irrigation water and the mapping of areas that are suitable for supplemental irrigation at the basin level, based on a land use map, DEM and long-term flow records at different subbasins. The computations of the flows before and after applying supplemental irrigation strategies allowed

evaluating: (i) the impacts of different supplemental irrigation strategies on stream flow; (ii) assessment of the water demand at each sub-basin; (iii) the spatial water allocation pattern; and (iv) the available and allocated water for each strategy. The application of these methods to upper KRB in Iran revealed that implementation of supplemental irrigation in the rainfed areas of the upper basin does not substantially reduce the average annual flow to the Karkheh reservoir, while it is expected to provide considerable yield and water productivity benefits.

Under normal flow conditions (30-yr average) a maximum of 2057 km^2, which represents 13 % of the rainfed crop areas and 28 % of the area suitable for supplemental irrigation, could be provided with supplemental irrigation in fall and spring. This would reduce the stream flow by 9 %. If environmental flow requirements are considered, this area would be reduced to 1444 km^2, while under drought conditions a maximum of 1013 km^2 could be provided with supplemental irrigation. The analysis clearly showed that the upstream subbasins are water limited, while the lower subbasins are limited with regards to suitable rainfed cropland. The methodology, the criteria and the scenarios may be refined further by including socioeconomic factors. In particular, the predicted changes in farm incomes under the proposed options may help influence policies for the reallocation of available water resources.

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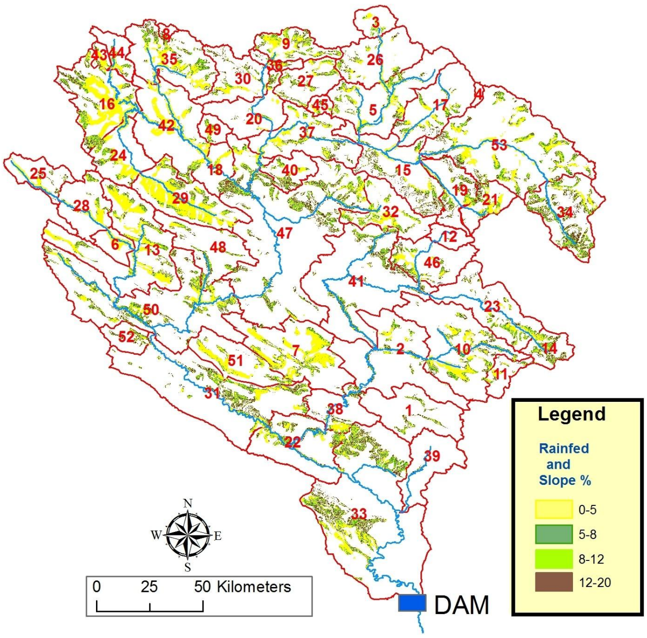

Fig. 1. Gauged subbasins and rainfed areas suitable for supplemental irrigation in upper Karkheh River Basin for four different slope classes.

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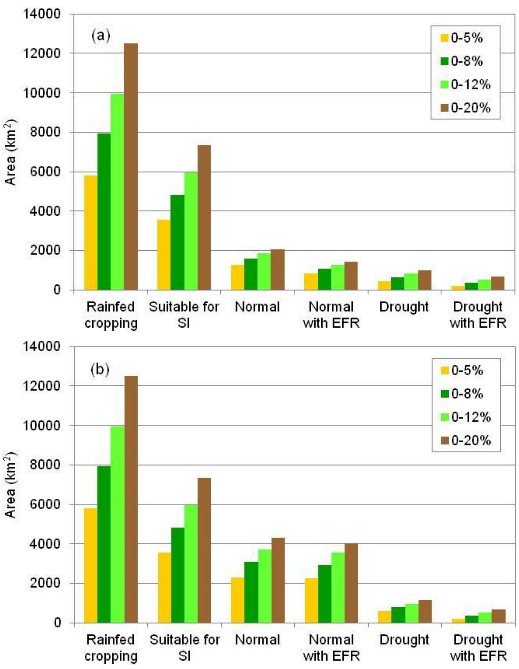

Fig. 2. Rainfed crop areas for four different slope classes for the whole upper Karkheh River Basin, rainfed crop areas suitable for supplemental irrigation (SI) (within 1-km buffer from the streams), and suitable areas that receive supplemental irrigation under the four flow scenarios; areas that receive both fall and spring irrigation **(a)**; areas that receive either fall or spring irrigation or both **(b)**.

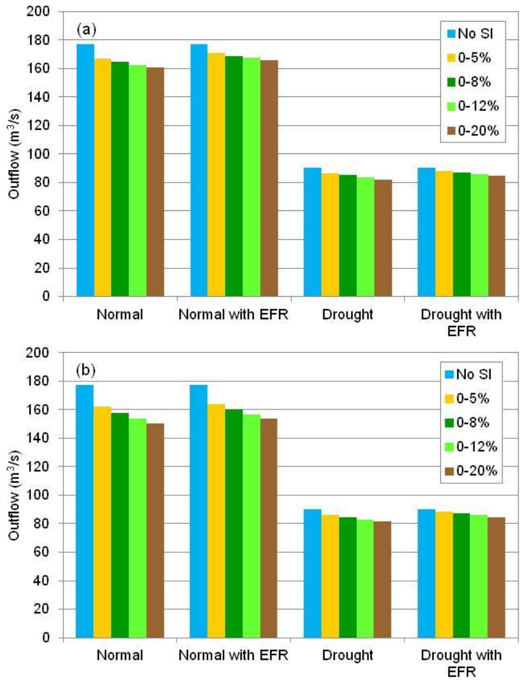

Fig. 3. Average annual outflow to Karkheh dam, before and after supplemental irrigation (SI) withdrawal for four slope classes and four flow scenarios: normal flow, normal with environmental flow (EFR), drought conditions, and drought with environmental flow; irrigating areas that receive both fall and spring irrigation **(a)**; irrigating areas that receive either fall or spring irrigation or both **(b)**.

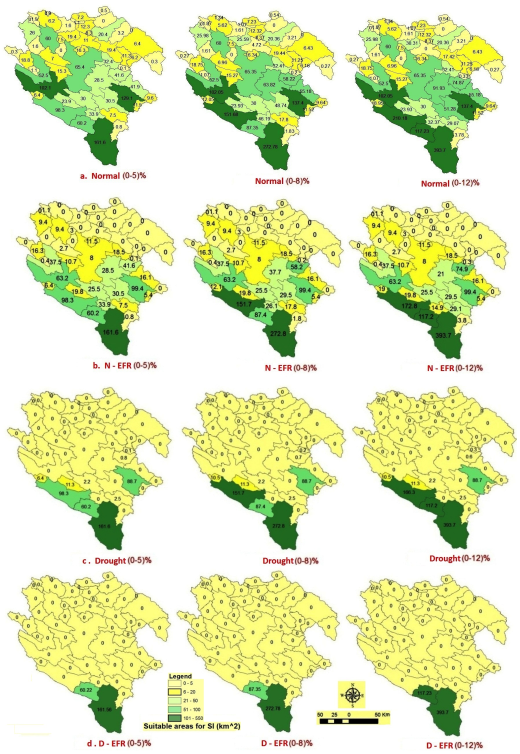

Fig. 4. Areas that could receive supplemental irrigation in fall and spring in the 53 subbasins of Karkheh River Basin, for four flow scenarios and three slope classes.