4.4. Satellite assessment of irrigation performance

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Traditionally, performance of irrigated agriculture has been expressed in terms of efficiencies based on observed flows in different points in the water distribution system, such as reservoir releases, main, secondary and tertiary canal, field, and plant. For example, the ratio of total water received at the field by farmers over the releases of a reservoir is defined as the system efficiency. The main objective of irrigation engineering has always been to increase those efficiencies. However, if a significant proportion of these "losses" are actually re-used elsewhere downstream, then improving efficiency may have counter intutitive results, such as depriving established users of their water supply. In such a situation, improving efficiency upstream would require new flows to be made available to existing downstream users.

To overcome these problems with efficiencies, Molden and Sakthivadivel (1999) described a conceptual framework for water accounting, based on inflows and outflows. The framework includes the assessment of system performance in terms of the Productivity of Water (PW), defined as the amount of water used to produce 1 kg of crop. Here we apply only PWprocess depletion[6], which refers to the amount of water transpired and evaporated to produce 1 kg of crop.

Recently, new technologies based on remote sensing (RS) have been introduced to monitor several components of the water balance. The main advantage of this approach is that large areas are covered, and that data is easily obtainable without extensive monitoring networks in the field. The SEBAL (Surface Energy Balance Algorithm for Land) algorithm (Bastiaanssen et al. 1998) estimates the energy balance based on remotely sensed images and estimates in actual evapotranspiration. The algorithm includes additional features to estimate crop production and soil moisture contents. For the four main irrigation systems in the Zayandeh Rud Basin, Iran, the SEBAL algorithm was applied, using NOAA images, and results were used to assess the performance of these systems.

Twelve images were selected for 1995, to represent a year in which water conditions were normal and likely to produce typical cropping conditions, and for each image the SEBAL algorithm was applied. SEBAL, the Surface Energy Balance equation, estimates the sensible heat flux from plants and this is used as the basis for estimating instantaneous evapotranspiration. Combined with maps of vegetated area determined using NDVI results, it is then possible to identify both the overall irrigated area and the degree of evapotranspiration.

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[6] Process depletion is that water actually transpired or evaporated at the field in the course of crop production.

4.4.1. Estimation of Irrigated Areas

Based on NDVI data alone it is possible to estimate irrigated area. These results are presented in table 4.4.

Table 4.4. Irrigated areas measured from maps and estimated from NOAA satellite images.

System	Designed Command Area (ha)	Measured Command Area (ha)	NOAA Estimated Area (ha)	Estimated Cropping Intensity (%)
Nekouabad Right Bank	13,500	20,532	16,631	81
Nekouabad Left Bank	48,000	38,863	30,313	78
Abshar Left Bank	15,000	52,370	38,754	74
Abshar Right Bank	15,000	22,565	16,247	72

With the exception of the Nekouabad Left Bank, gross cropped area reported as irrigated and the estimates from NOAA indicate cropped areas are larger than designed, because there is significant groundwater use that increases the area that can be irrigated. For this reason, the use of secondary data alone is insufficient to estimate the actual productivity of the areas, and SEBAL analyses are required to interpret data available from satellites.

Figure 4.11 shows an example of the results from SEBAL for April 1995. April represents a transition month with tail-end areas still having winter crops such as wheat and barley, and head-end areas beginning to have summer crops such as rice, fodder and maize. Irrigated areas can be clearly distinguished from the NDVI map with values of 0.20 and higher.[7] High intensities can be found for the Abshar systems, reflecting the dominant cropping pattern with mainly winter crops. Interesting are also the relatively high intensities for the Rudasht-East system, indicating that during spring, a reasonable amount of water is reaching this downstream area.

The estimated crop productions can be considered as the integrating parameter of water and crop management. The Abshar system is clearly the most productive system in April, with daily biomass production values for some areas of 100 kg ha^{-1} d^{-1}. For a crop with an active growing period of 120 days, this translates into 12,000 kg ha^{-1} biomass. The conversion factors from biomass to harvested product depends on crop, variety, and plant physiological condition, and values range from 10-30 percent, resulting in an actual yield of 1,200–3,600 kg ha^{-1}.

Finally, the estimated soil moisture contents show that most soils are reasonably wet, even soils without any crop (low NDVI). Also areas with an intensive cropping pattern (high NDVI) but moderate soil moisture content can be observed, indicating that irrigation is required for these areas at the time of image acquisition.

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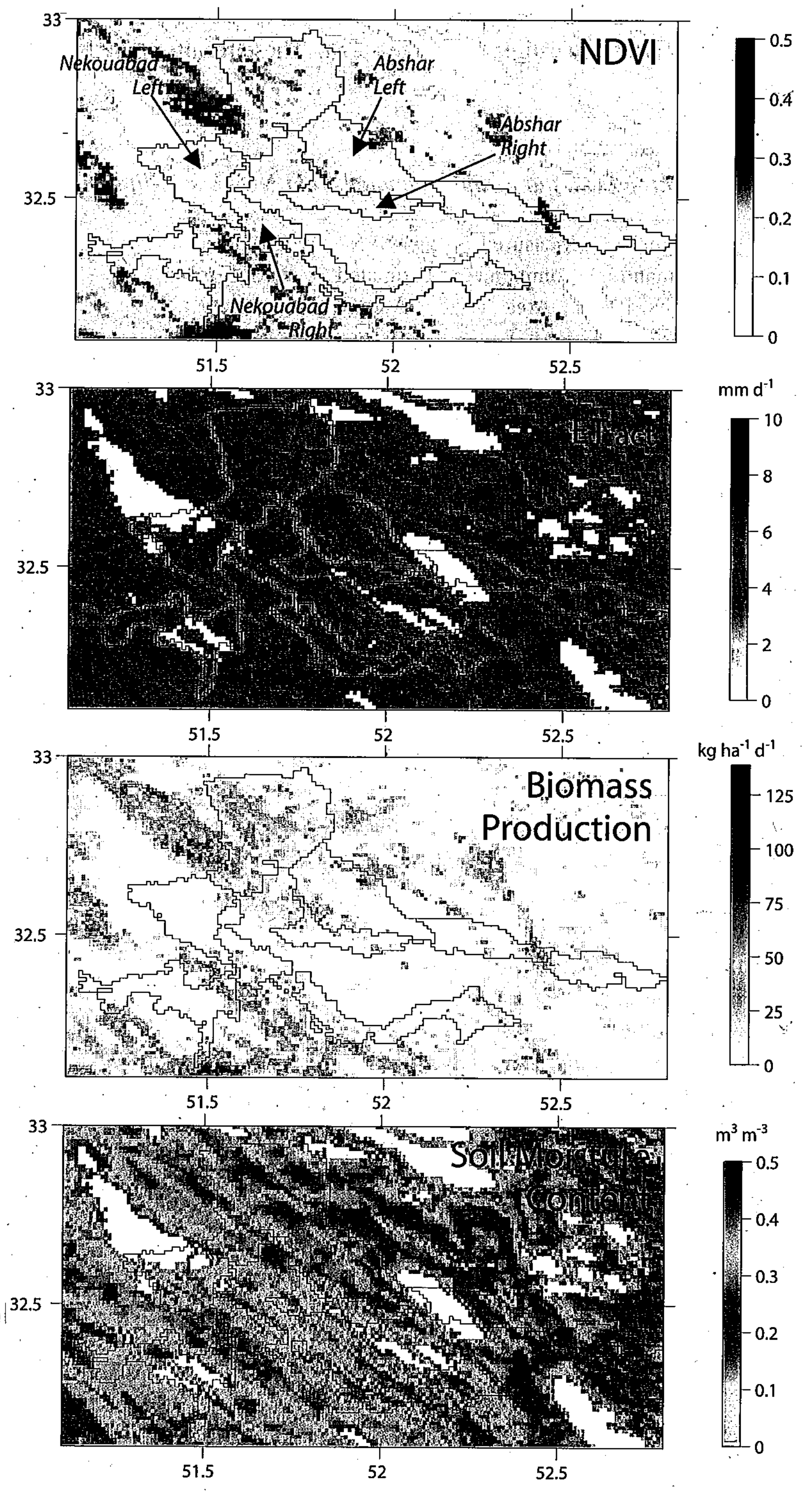
[7] This value of NDVI for crops is rather low, and can be explained by low cropping intensity, with a high degree of fallow within an individual pixel at the time of image acquisition.

Figure 4.11. Result of the SEBAL analyses for April 1995.



4.4.2. Monthly Variations in Irrigation Performance

Monthly NDVI values for the four main systems are shown in figure 4.12. The dual cropping pattern can be observed with "high" NDVI values from March to May and from August to October. Lower values in June and July are the result of the end of the growing season for spring crops (wheat) and the start of the summer crops (rice). For Abshar-Right, and especially Abshar-Left, the peak for summer crops is lower as a result of the smaller area cultivated with rice.

Potential evapotranspiration (ET_{pot}) shows a similar pattern for all systems (figure 4.12.), with peak values for mid-summer of around 8 mm d^{-1}. ET_{act} reflects again clearly the difference between the Nekouabad and the Abshar systems, with the latter having a cropping pattern existing mainly out of winter crops harvested in June, while Nekouabad systems have sufficient water to allow good crop growth throughout the summer.

Crop growth peaks in May, when climatic conditions in terms of radiation are optimal and sufficient water is available from precipitation, soil moisture storage, and irrigation. Soil moisture storage fluctuations show high values in May as a result of precipitation and irrigation. Low values can be seen for Abshar during the period July-October as a result of water extractions by crops and lack of sufficient irrigation water to replenish soil moisture.

4.4.3. Annual variations in Irrigation Performance

The results for four irrigation systems were aggregated to annual total crop areas (table 4.5) by taking the maximum NDVI value for each pixel in April and September and assuming that all values higher than 0.2 were cropped.

Releases for irrigation differ substantially from system to system. Figures presented here relate to the whole system area, rather than the areas served by surface irrigation. Converting these values to the official command areas leads to application rates between 1,000 and 1,500 mm ha^{-1}. Precipitation was considered to be similar for all areas, as the distance between systems was limited. Because precipitation is low throughout the area, it has relatively little impact on annual water balance.

The overall water balances for the systems are not closed (table 4.5) and three of the four systems show a water deficit. The apparent water surplus for Nekouabad Left Bank can be explained by the new offtake canal from Nekouabad Left Bank main canal to the new Borkhar system. It is unclear how much water was actually delivered to Borkhar, so the water supply to Nekouabad Left Bank only could not be determined.

The main question for the three water deficit systems is, "where is this other water coming from?" Two sources can be identified. First of all, a certain amount of water is extracted directly from the river, which is not included in the water balance. Second, groundwater irrigation is extensively applied in the area. Quantitative information about these two additional inputs in the systems is lacking, but can be estimated as the missing term in the water balance.

Figure 4.12. Monthly values of NDVI, ET_{pot}*,* ET_{act}*, biomass production, and soil moisture contents, for the four systems.*

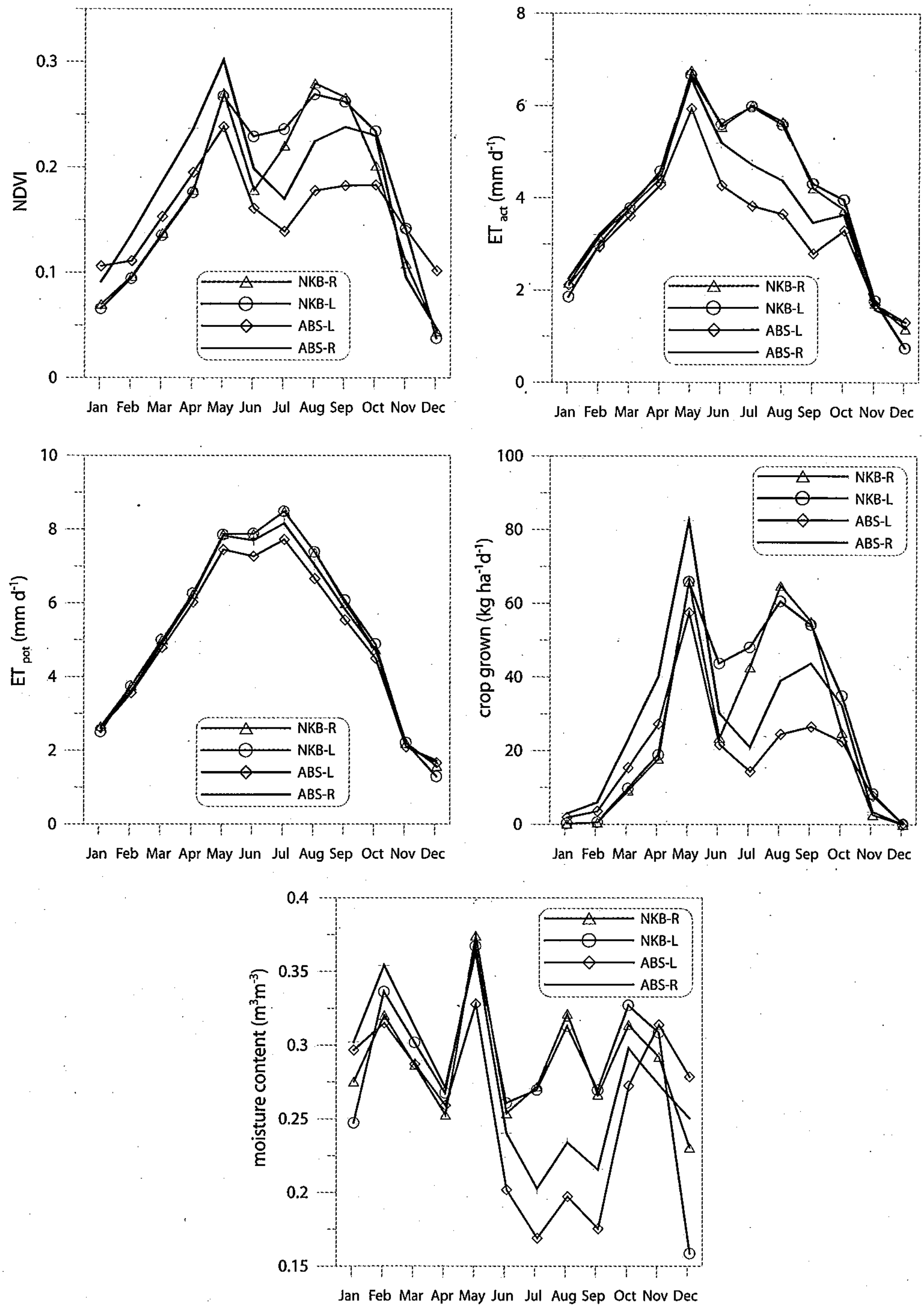


Table 4.5 Annual water balance and productivity of water (biomass production / water supply). MCM = 10^6 m^{-3}.

System	ETact		Releases		Precipitation		Balance		Biomass		PW_{depl}
	MCM	mm	MCM	mm	MCM	Mm	MCM	mm	M kg	kg ha^{-1}	kg m^{-3}
NKB-R	243	1,183	181	882	25	123	-37	-178	193	9,388	0.79
NKB-L	459	1,180	477	1,227	48	123	66	170	409	10,528	0.89
ABS-L	484	924	230	439	64	123	-190	-362	356	6,806	0.74
ABS-R	246	1,088	201	891	28	123	-17	-74	223	9,894	0.91

For Abshar-Left, this combined groundwater and unofficial water extraction is about 190 mm (table 4.6). The designed command area of Abshar Left Bank is 15,000 ha, while the cropped area, as determined by NOAA, is almost 39,000 ha. It is clear that the additional areas are irrigated by groundwater. Nekouabad Right Bank and Abshar Right Bank show an annual deficit of 178 and 74 mm, respectively. The designed command area for these systems are 13,500 and 15,000 ha, while actual cropped areas are higher (table 4.4). Using the data from the three deficit systems, a simple linear regression was developed ($r^2 = 0.87$) to assess the relationship between groundwater extractions, designed and actual cropped area:

$$\text{Groundwater exraction} = -132 \cdot \frac{\text{designed area}}{\text{cropped area}}$$

Finally, these results can be used to explore the productivity of the systems. As described before, we used the Productivity of Water, expressed as the biomass production over the amount of water depleted by ET_{act}. Abshar Left Bank appears to be the least productive of the four systems. Groundwater quality in the Zayandeh Rud is much poorer than surface water, so for Abshar Left Bank, with its high percentage groundwater irrigation, this PW is low. For Nekouabad Left Bank, with limited groundwater irrigation, PW is high. Although groundwater extraction seems high for Abshar Right Bank, PW is not low. Probably, the negative values in the water balance for this system are mainly caused by unaccounted water extraction from the river rather than from groundwater.

Table 4.6. Comparison between the current study (NOAA) and a supply and demand study based on Cropwat and cropping patterns.

System	NOAA		Accounting	
	MCM	mm	MCM	mm
Nekouabad Right Bank	-37	-178	34	166
Nekouabad Left Bank	66	170	66	170
Abshar Left Bank	-190	-362	-74	-141
Abshar Right Bank	-17	-74	75	332

Source: Sally et al..2001.