

Irrig Sci (2010) 28:371–385
DOI 10.1007/s00271-009-0199-3

ORIGINAL PAPER

A remote sensing-based irrigation performance assessment: a case study of the Office du Niger in Mali

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Received: 7 April 2009 / Accepted: 23 October 2009 / Published online: 14 November 2009
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Abstract The irrigation performance of the Office du Niger in Mali, a large-scale rice-based irrigation scheme, was analysed with the use of remote sensing technology. The major advantage of remote sensing derived data over field measured data is that it provides system-wide, spatially distributed and objective information. Four irrigation performance indicators, entirely based on remote sensing, were applied at different organisational levels of the system. The surface energy balance algorithm for land model was applied to high-resolution Landsat images to calculate rice production and water consumption spatially. These maps were used to analyse the productivity of water, the uniformity of water consumption and head-/tail-enders issues at the level of the system, the five administrative zones and smaller management units (*casiers*). The sustainability of the system was assessed using a long-term time series of the normalised difference vegetation index. The results were discussed and interpreted with the irrigation managers of the Office du Niger. The analysis provided new insights in the performance of the system such as existing head–tail patterns in water consumption and rice yields.

Introduction

The growing pressure on fresh water resources has been widely acknowledged, and there is a need for water resources to be better managed (e.g. Rockstrom et al. 2007; Comprehensive Assessment of Water in Agriculture 2007). Whereas historically there was sufficient water for irrigation, pressure is now mounting to reduce the amount of water allocated to agriculture, to provide more for other sectors. Improved water management is therefore required for an efficient use of the available resources to maximise the productivity of water. An effective service to irrigators in terms of adequate and reliable water supplies is a key determinant in sustaining and increasing agricultural production (Molden et al. 2001).

Irrigation performance assessment is considered an important management tool to implement, monitor and evaluate activities for water delivery services. Murray-Rust and Snellen (1993) and Molden et al. (2001) describe several ways how, and for which purpose, irrigation performance tools can be applied. *Operational* performance assessments describe the functioning of operational management processes. A *strategic* performance provides information on whether an organisation is performing and using the available resources efficiently. A *diagnostic* performance assessment is used to understand differences within a system and locate areas for system improvement and rehabilitation. Finally, a *comparative* performance assessment can be used to set benchmark standards and detect processes in a system that lead to higher performance. A large number of performance indicators used to quantify irrigation performance is available (Bos et al. 2005). They link socio-economic, institutional, financial and technical aspects of irrigation management to the physical processes of water distribution, water

Communicated by J. Kijne.

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consumption and crop production. The indicators that can be applied at various scales from plot level to system level require different input data, depending on the scale and complexity. Moreover, the indicators should have a scientific basis, should be easy to use, quantifiable, unbiased and cost effective (Bos 1997). Inputs that are required to assess the physical irrigation performance include measurements of different terms of the water balance such as discharge, evapotranspiration, effective precipitation, as well as measurements of crop yields, and estimates of irrigated area and cropping intensities. The application of indicators at the lower hierarchical scale in an irrigation system requires expensive and labour intensive field campaigns. Moreover, it is virtually impossible to obtain a data set that covers the total system. This limits the possibilities to analyse, for example, the equity of water distribution among users in different parts of the system. The implementation of irrigation performance indicators as a tool for irrigation management is inhibited by the costs and effort that need to be made to obtain system-wide and detailed data sets.

In recent decades, the possibilities to use spatial remote sensing data have been investigated. Major advantages of remote sensing derived data over field measured data are that they are objective and collected systematically and system wide. Another advantage is that the information can be analysed at different scales (Bastiaanssen et al. 2000). Bastiaanssen and Bos (1999) provide an overview of performance indicators that can be derived from remote sensing data. Some of the indicators can only be derived from remote sensing data, while others are combined with field measurements. Roerink et al. (1997) was amongst the first to analyse irrigation performance indicators of an irrigation district in Argentina by combining measurements of water deliveries and a high-resolution remote sensing derived map of daily evapotranspiration rate. A time series of low-resolution images was used to assess a set of performance indicators in a large irrigation district in Brazil. Seasonal estimates of potential and actual evapotranspiration were combined with in situ measured irrigation water deliveries and precipitation to spatially calculate the relative water supply and the overall consumed ratio (Bastiaanssen et al. 2001). These were followed by other studies in Sri Lanka, Iran, Turkey, India and Pakistan where remote sensing derived maps were combined with in situ measurements to evaluate performance indicators such as irrigation efficiency (Bandara 2003), water productivity, relative water supply (Akbari et al. 2007), crop water deficit, relative evapotranspiration (Karatas et al. 2009), equity, uniformity and adequacy (Ahmad et al. 2009). Time series of remote sensing derived vegetation indices are also used to analyse irrigation performance in terms of sustainability or intensity of crops cultivated and irrigated (Thiruvengadachari and Sakthivadivel 1997).

The objective of this paper is to provide a low-cost remote sensing-based methodology that can be applied to make a rapid scan of the performance of an irrigation system. Although the remote sensing techniques have been thoroughly tested and validated, few operational applications of irrigation performance assessment based on remote sensing data are known. Moreover, most studies are a combination of in situ measurements and low-resolution remote sensing maps, whereas this paper presents an application based on remote sensing data only and at a high level of detail. The higher resolution allows spatial analysis of the performance indicators up to tertiary level. This study will focus on strategic and diagnostic performance indicators with the purpose of detecting areas with good and poor performance and to provide strategic information for the improvement of the overall system performance. A long-term time series of NDVI maps were used to assess the agricultural intensity of the system. The surface energy balance algorithm for land (SEBAL) model was applied to twelve high-resolution satellite images taken by the Landsat sensor during the 2006–2007 irrigation season to obtain maps of seasonal actual evapotranspiration and biomass production. These were used to analyse the uniformity of water consumption and the productivity of water at different spatial scales in an irrigation system. The Office du Niger, a large-scale, rice-based irrigation system along the Niger river in Mali was used as a study area. The planned expansion of commercial sugarcane estates and upstream irrigation areas, as well as the planned expansion of the Office du Niger in the future, force the scheme management to improve water productivity. The results of this study were discussed with irrigation managers from different levels in the Office du Niger. These discussions have provided feedback regarding the limitations and advantages of the proposed method as well as recommendations to improve the methodology. Possible future applications in the specific context of the Office du Niger are also outlined.

Methods and materials

Introduction

Four indicators were used to analyse the irrigation performance in the Office du Niger using only remote sensing data:

1. *cropping intensity* from a long-term normalised difference vegetation index (NDVI) time series (July 1998–June 2008);
2. *productivity of water* (WP), defined as estimated rice yield divided by water consumption from evapotranspiration;

3. *uniformity*, the coefficient of variation (c_v) of water consumption by evapotranspiration to evaluate the uniformity of water consumption and
4. *head–tail performance indicator*, for assessing the spatial pattern of water consumption, rice yields and water productivity among irrigators in head and tail reaches.

This section continues with a description of the Office du Niger and is followed by the methodology to spatially assess biomass production and water consumption from actual evapotranspiration based on satellite images and the SEBAL algorithm. Thereafter, the methodology to assess the earlier mentioned performance indicators will be outlined.

Study area

The Office du Niger, situated in the Ségou region of Mali, is one of the oldest and largest irrigation schemes in West Africa. It was developed during the French colonial time in the 1920s. Initially, the idea was to irrigate one million hectare within 50 years with the objective of supplying cotton to the French cotton industry, and to grow rice to ensure food security in the Sahel regions and French colonies in West Africa (Ertsen 2006). Nowadays, with its 80,000 ha of paddy rice, it is of great importance for the national food security. It provides approximately 465,000 tons of paddy each year which contributes up to 40% to the national production (Aw and Diemer 2005).

Water delivery and the irrigation infrastructure for the whole irrigated system are managed by a central institution also called *Office du Niger*, which has its headquarters in Ségou. The system is divided into five administrative zones responsible for land and water management in their part of the irrigation scheme (see Fig. 1). Each administrative zone has a committee which farmers can join to participate in the management at secondary level. The zones are subdivided into *casiers*, which are further sub-divided into tertiary blocks which, on average, represent ten farmers. The irrigation water is diverted from the Niger River at the *Barrage de Markala* and then flows into two abandoned river branches (*Falas*). Water is diverted by gravity through a hierarchic network of canals that lead water directly from the Falas. The network consists of primary (*distributeur*), secondary (*partiteur*) and tertiary (*arroiseur*) canals. Farmers conduct irrigation and drainage of individual rice fields by, respectively, extracting from or discharging water to the field canals which are connected to the tertiary canals and drains (Vandersypen et al. 2006).

There are two major growing seasons: *la Saison* and *la Contre-Saison*. The main rice growing season is during *la Saison* which coincides with the rainy season and extends

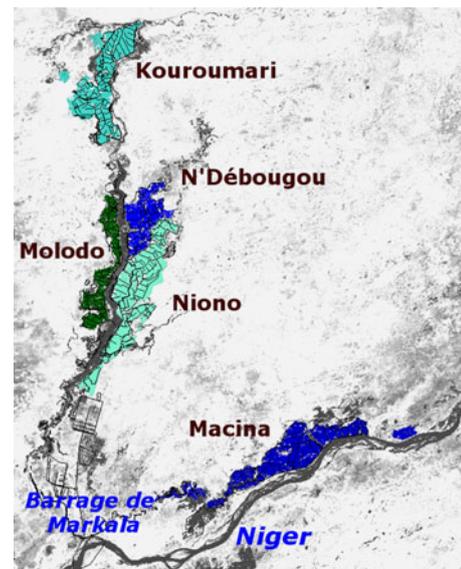


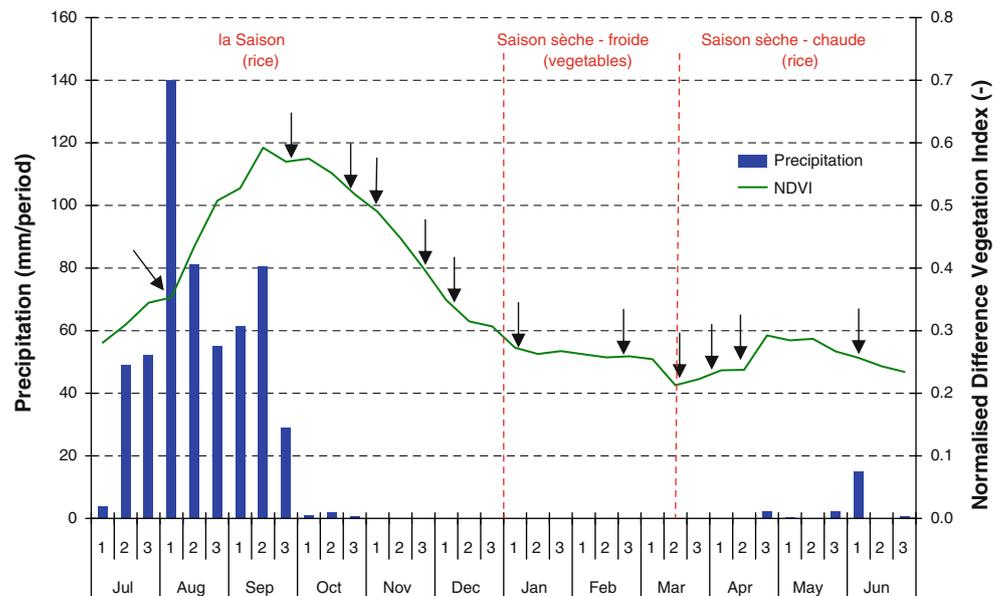
Fig. 1 Layout of the Office du Niger in Mali. The five administrative zones are indicated as well as the Barrage de Markala in the south-west corner and the Niger running south of the system

from approximately June to December (see Fig. 2). The second growing season is during the dry season or *la Contre-Saison*. This season is divided into a relatively colder period, *Saison Sèche froide*, when vegetables are cultivated (January to March) and a very hot season, *Saison Sèche chaude*, when rice is cultivated (March to June). During *la Saison*, water is abundant and the entire irrigation network is continuously filled with water. Water supply is on demand and farmers can irrigate as long as they have paid a seasonal contribution for the use of the water (*redevance*). In recent years, the government has promoted the second rice season by lowering the *redevance*. In the dry season, only a part of the system can be irrigated due to lower discharge rates in the Niger.

SEBAL and the surface energy balance

Since the early 1980s, algorithms have been developed that can quantify the different terms of the energy balance using thermal infrared satellite imagery and standard meteorological measurements. Examples of these models, with varying degrees of complexity, include the two-source energy balance (TSEB) (Norman et al. 1995), surface energy balance algorithm for land (SEBAL) (Bastiaanssen et al. 1998), simplified surface energy balance index (S-SEBI) (Roerink et al. 2000), surface energy balance system (SEBS) (Su 2002), amongst others. The models have in common that, with different complexity, they calculate the *actual* evapotranspiration as the residual from the surface energy balance. More recently, the SEBAL algorithm was updated with a module to calculate biomass

Fig. 2 Precipitation measured at the meteorological station in Ségou and the spatial average of the green vegetation index (NDVI) in the Office du Niger between July 2006 and June 2007. Black arrows indicate the Landsat image acquisition days



production spatially (Bastiaanssen and Ali 2003; Zwart and Bastiaanssen 2007).

In this study, the SEBAL algorithm was applied on a time series of twelve Landsat7 images to calculate biomass production and actual evapotranspiration spatially for the 2006–2007 agricultural season. Since 1984, the Landsat programme has been systematically acquiring and archiving high-resolution satellite images. Since early 2009, all archived images can be freely obtained from the archives through the GLOVIS portal of the United States Geological Survey (USGS).¹ The spatial resolution of the Landsat images is 30 m for the six visible and near-infrared bands, and 120 and 60 m for the thermal band of Landsat5 and Landsat7, respectively. Both satellites have a recurrence time of 16 days. The Office du Niger is located centrally on one single Landsat scene, (path 198, row 50, see Fig. 3). Twelve cloud-free, gap-filled Landsat7 images were selected. In Table 1, the Landsat image acquisition dates are depicted. During the rainy period from May to September, a limited number of images were available, whereas the rest of the season shows a good temporal coverage (see Fig. 2).

Surface energy balance algorithm for land requires spatial inputs of the surface temperature, surface albedo and the NDVI, which are derived from the Landsat images (see Fig. 4). A major advantage of the SEBAL algorithm is that the calculations are performed independently from the land use. Meteorological measurements of air temperature, relative humidity and wind speed were obtained from the Ségou meteorological station which is located approximately 30 km southwest from the intake of the system

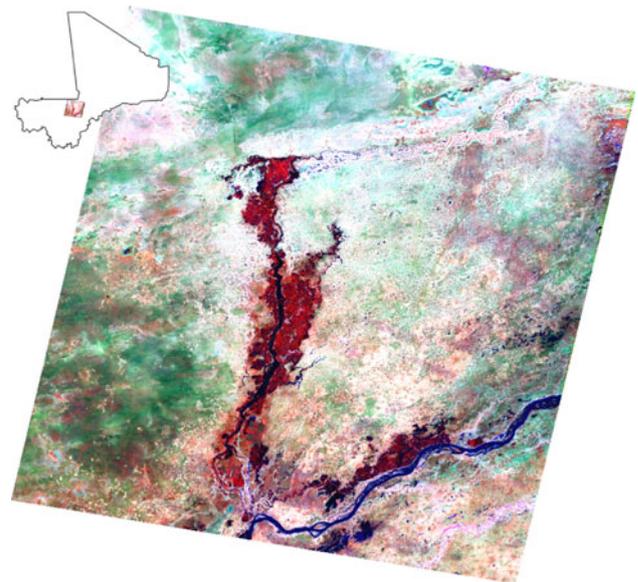


Fig. 3 Location of the Office du Niger in Mali on a Landsat7 image acquired on October 5, 2006. The image is depicted in the false colour band combination 4-5-3. The red colours indicate green vegetation. The Niger river is located on the southeastern part of the image

(Barrage de Markala). Spatial measurements of incoming solar radiation were obtained from the down-welling surface short-wave radiation flux (DSSRF) product that is provided by the land surface analysis satellite applications facility (LSA SAF).² SEBAL first calculates the daily evapotranspiration and biomass production for the day that the image was acquired using daily average meteorological data. To interpolate the results between days of acquisition, the SEBAL model is re-applied with meteorological data

¹ <http://glovis.usgs.gov>

² <http://landsaf.meteo.pt>

Table 1 Landsat image acquisition dates, the period for which it is representative and the season for which it is considered

Landsat acquisition date	Period	Season
2 Aug 2006	1 Jul–31 Aug	la Saison
5 Oct 2006	1 Sep–13 Oct	la Saison
21 Oct 2006	14 Oct–29 Oct	la Saison
6 Nov 2006	30 Oct–14 Nov	la Saison
22 Nov 2006	15 Nov–30 Nov	la Saison
8 Dec 2006	1 Dec–24 Dec	la Saison
9 Jan 2007	25 Dec–2 Feb	Saison Sèche—froide
26 Feb 2007	3 Feb–6 Mar	Saison Sèche—froide
14 Mar 2007	7 Mar–22 Mar	Saison Sèche—chaude
30 Mar 2007	23 Mar–7 Apr	Saison Sèche—chaude
15 Apr 2007	8 Apr–12 May	Saison Sèche—chaude
10 Jun 2007	13 May–30 Jun	Saison Sèche—chaude

that are averaged for the period that is considered (see Table 1). Certain biophysical parameters, such as the NDVI, surface albedo, bulk surface resistance and evaporative fraction, are kept constant and assumed to be representative for the period. For more details on the SEBAL algorithm, reference is made to Bastiaanssen et al. (1998) and (2005) for updates of the algorithm. The module to calculate biomass production from satellite images using the SEBAL algorithm is described in Bastiaanssen and Ali (2003) and Zwart and Bastiaanssen (2007). The latter also details the methodology to interpolate the daily results between the periods.

The boundaries of the official perimeter of the irrigated areas in the Office du Niger were made available in GIS format. For the two major rice seasons, the cropped areas were determined using an unsupervised classification. The classification was based on the time series of the Landsat NDVI images in the defined periods (see Table 1). The isolated sugarcane areas located halfway between the Barrage de Markala and Niono were included separately. The cropped area, mainly vegetables, in the Saison Sèche—Chaude was not analysed since (1) the vegetable fields are too small to be distinguished on the 30 × 30 metre pixels, and (2) only two Landsat images at the start and the end of the short season were available. This study will therefore focus on rice cultivation in la Saison (July to December) and in the Saison Sèche—chaude (March to June).

Irrigation performance indicators

Cropping intensity

The normalised difference vegetation index (NDVI) is a measurement of the “greenness” of an area and is defined

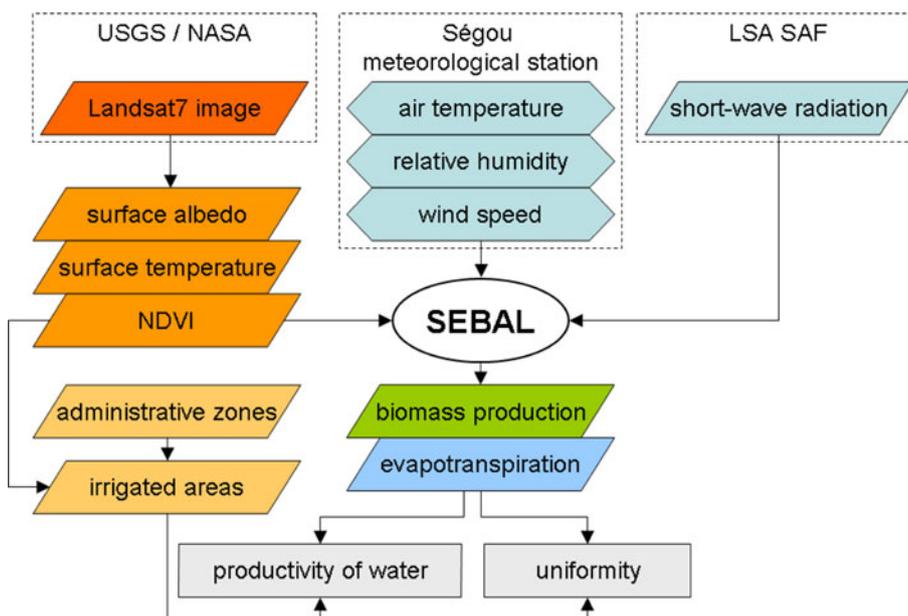
as the difference between radiation in the near-infrared and red spectra divided by the total radiation in near-infrared and red spectra (Tucker 1979). As such, the NDVI is an indicator of the presence and intensity of agricultural activities (Thiruvengadachari and Sakthivadivel 1997). A long-term time series of NDVI images is considered to determine whether there is an increase or a decrease in the intensity of agricultural activities. NDVI maps based on the SPOT-vegetation sensor have a resolution of 1 × 1 kilometre and are freely available for 10-day periods since July 1998,³ thus providing a time series of ten consecutive years. The NDVI maps were downloaded and imported for an area covering the entire irrigation system. To analyse the sustainability of the system in terms of agricultural intensity, a linear regression was performed on the NDVI time series for (1) la Saison, running from the 1st 10-day period in July till the 3rd 10-day period in December, (2) Saison Sèche—froide, running from the 1st 10-day period in January to the 1st 10-day period in March and (3) Saison Sèche—chaude, from the 2nd 10-day period in March to the 3rd 10-day period in June (see Fig. 2). A negative slope for the ten seasons considered indicates that the intensity of agricultural activities is degrading, whereas a zero or positive trend indicates that the irrigation systems manage to divert water to match demand. The analysis was performed at the level of the system and of the five administrative zones by averaging the NDVI for the system and for each zone separately. The casiers were not analysed individually since their areas are too small considering the 1 × 1 kilometre resolution of the NDVI images.

Productivity of water

The productivity of water is defined in this study as the total estimated rice yield divided by the seasonal water consumption from actual evapotranspiration. It is an important indicator to locate areas where water resources are being used efficiently for crop production and where they are being wasted (Comprehensive Assessment of Water in Agriculture 2007). The dry yields are traditionally being obtained from dry biomass production estimates (Bio in $kg\ ha^{-1}$) by applying a crop-specific harvest index (H_i). The fresh marketable yields (Y in $kg\ ha^{-1}$) are estimated by including the plant water content (θ_p). The H_i of rice under optimal conditions varies between 0.40 and 0.50 and the θ_p is between 15 and 20% (Doorenbos and Kassam (1979). It is known, however, that more modern rice varieties are potentially more efficient (more rice grains, less green vegetation), but H_i may decrease due to water, nutrient or temperature stress. The water productivity (WP) of rice can now be calculated using:

³ <http://free.vgt.vito.be>

Fig. 4 Visual representation of the SEBAL inputs that are required to calculate biomass production and actual evapotranspiration from Landsat images, and then the performance indicators



$$WP = \frac{\text{Bio} \cdot H_i / (1 - \theta_p)}{\text{ET}} = \frac{Y}{\text{ET}} (\text{kg m}^{-3}) \quad (1)$$

where ET equals the seasonal water consumption from evapotranspiration in $\text{m}^3 \text{ha}^{-1}$. The maps of cropped areas during the two rice seasons will be used to select pixels classified as rice. The spatial estimates of WP will be analysed for both seasons at the scale of the five zones and the casiers in the zone of Niono.

Uniformity

In an ideal system, where water is distributed equally and timely among all irrigators, and where other agronomic practices are optimal, the water consumption patterns in such a system should be homogeneous throughout a system. However, under actual field conditions, several factors such as bad maintenance of canals and structures, inadequate management, but also soil type, water quality, fertilization may influence water consumption from field to field and from zone to zone. Unequal distribution of water can often be directly linked to poverty (Hussain and Hanjra 2004). Visualising head–tail problems and designing measures to promote a more equal distribution can have a strong impact on the livelihoods of farmers located at the tail-ends. Several authors have used the coefficient of variation (c_v), defined as the standard deviation (σ) divided by the mean (μ), as an objective performance indicator to analyse the uniformity of water consumption in a system (Bastiaanssen et al. 1996; Roerink et al. 1997). More recently, Zwart and Bastiaanssen (2007) compared eight wheat systems worldwide and used

the c_v of water productivity as a comparative indicator for the scope of improvement in each wheat system. In this study, the c_v of actual evapotranspiration will be used to analyse the uniformity of water consumption in the five zones and in the casiers of the Niono zone. The analysis will be performed for rice cultivation during la Saison only since it is the only season when the area is fully cropped. During the second rice season, only part of the area is cropped and the calculations for c_v will not be possible.

Finally, potential head-/tail-enders problems are analysed as a second indicator of uniformity. Water may fail to reach the irrigators at the tail of a canal due to poor condition of control structures, illegal water use by irrigators, or poor irrigation management (see e.g. Molden et al. 2001). The spatial estimates of water consumption and rice yields provide objective and unbiased data to quantify potential head–tail problems. Head–tail end issues are visualised at different management levels (system, zones, casiers). The area of each management unit is divided into ten equal areas measured from the intake (see Fig. 7) to determine which field is located at the head of the system and which at the tail-end. The rice yields and the water consumption are then averaged for each of the ten equal areas and visualised in a graph. For the Office du Niger, the head–tail performance indicator is analysed for the four zones that are hierarchically supplied with water. Macina receives its water through a different canal directly from the Barrage de Markala. A major advantage of this method is that it can be applied rapidly without knowing the exact location of the canals, and it allows a spatial analysis of consumption and production patterns.

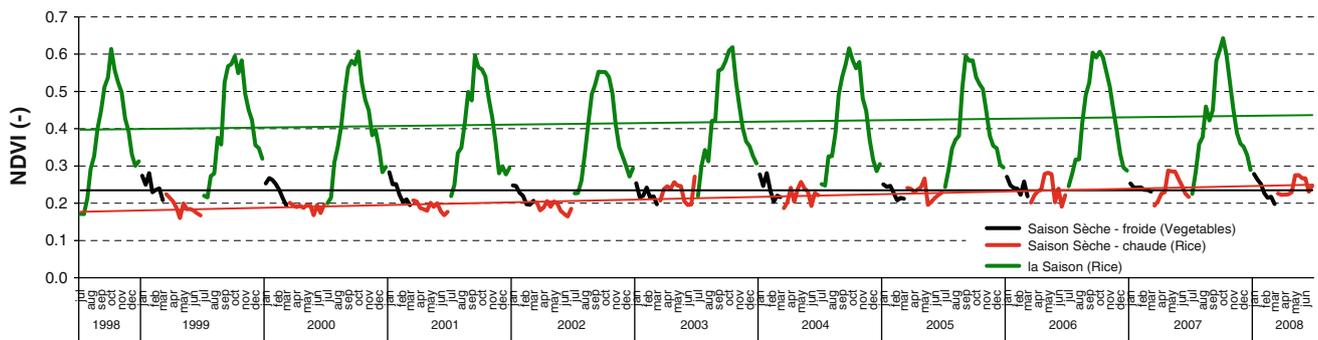


Fig. 5 Ten yearly profile of the average NDVI of the Office du Niger between July 1998 and June 2008. The three different agricultural seasons are indicated in *different colours*. The *straight lines* show the linear regression through the time profile for each of the three seasons

Discussions with the irrigation managers

The results of the analysis of the performance indicators were presented to the managers at the different levels of the management structure, including the central management, the directors of the zones and the managers of the casiers in the zone of Niono. The purpose of these meetings was (1) to introduce the Office du Niger to the possibilities of remote sensing for irrigation management, (2) to provide interpretation of the results, (3) to obtain feedback regarding the advantages and limitations of the methodology and (4) to discuss the future possibilities of integrating remote sensing for the operation and evaluation of irrigation management. The results of the discussion are presented in the following sections.

Costs

An important objective of this research was to provide a cost-effective tool. The direct and indirect costs are discussed and compared with similar remote sensing studies related to irrigation performance and irrigation water management.

Results and discussion

Cropping intensity

In Fig. 5, the profile of the NDVI time series averaged for the entire Office du Niger system is shown. A repetitive pattern is seen during La Saison in each year. In June, the crop develops and the measured green cover increase from around 0.20 to 0.60. This is followed by a vegetative period of several 10-day periods. During the period of maturation and harvest, the average NDVI again decreases. The colder period in Saison Sèche—froide shows a less distinctive pattern, which may be caused by the mix of crops

and their difference in planting date and length of growing season. The second rice crop during Saison Sèche—chaude is (almost) absent in the first 4 years, but can be detected in the years following 2003. The intensity (peaks of the NDVI up to 0.28) is much lower than in the first season (peaks up to 0.64), but this is mainly caused by the fact that approximately only a quarter of the total area of the Office du Niger is cropped.

A linear regression was performed for the three seasons that were distinguished, and the slopes of the regression lines were considered to determine the change in cropping intensity of irrigated agriculture in the five zones, and in all zones combined (see Table 2). From the slopes, it can be concluded that irrigated agriculture in the Office du Niger is sustainable. The average NDVI increased slightly during la Saison ($+11 \times 10^{-5}$), and a sharper increase is seen during the Saison Sèche—chaude ($+20 \times 10^{-5}$). During the Saison Sèche—froide, the average NDVI remains constant ($+0.1 \times 10^{-5}$). If the zones are considered separately, it can be seen that all five zones depict an increase in cropping intensity during la Saison, varying from 7.0×10^{-5} in Molodo to 15×10^{-5} in Macina. Each year, between 75 and 90% of all precipitation usually occurs during this season, varying from 250 mm in July–December 2005 to 600 mm in July to December 1999 (source: TRMM monthly precipitation products⁴). These large differences appear to have no influence on the crop development, which indicates that sufficient irrigation water is available to produce rice during la Saison. It must be noted that at this scale, it is not possible to distinguish between rice crops and weeds which mainly grow in waterlogged areas during la Saison. Although weeds are not widely spread through the entire system, in certain areas, the actual rice cropping intensity may be lower and therefore not reflected in these results.

⁴ <http://neo.sci.gsfc.nasa.gov> (monthly precipitation products from the TRMM sensor).

Table 2 Slope of the linear regression through the 10-year NDVI time series averaged per zone

Zone	la Saison (Jul–Dec)	Saison Sèche—froide (Jan–Mar)	Saison Sèche—chaude (Mar–Jun)
Macina	$+15 \times 10^{-5}$	-2.5×10^{-5}	$+11 \times 10^{-5}$
Niono	$+13 \times 10^{-5}$	$+8.0 \times 10^{-5}$	$+32 \times 10^{-5}$
N'Debougou	$+8.1 \times 10^{-5}$	$+4.2 \times 10^{-5}$	$+31 \times 10^{-5}$
Molodo	$+7.0 \times 10^{-5}$	-1.9×10^{-5}	$+28 \times 10^{-5}$
Kouroumari	$+7.2 \times 10^{-5}$	-7.3×10^{-5}	$+6.7 \times 10^{-5}$
Office du Niger	$+11 \times 10^{-5}$	$+0.1 \times 10^{-5}$	$+20 \times 10^{-5}$

A positive or zero slope indicates that cropping intensity remains constant or increases, whereas a negative slope indicates that agricultural activities decrease

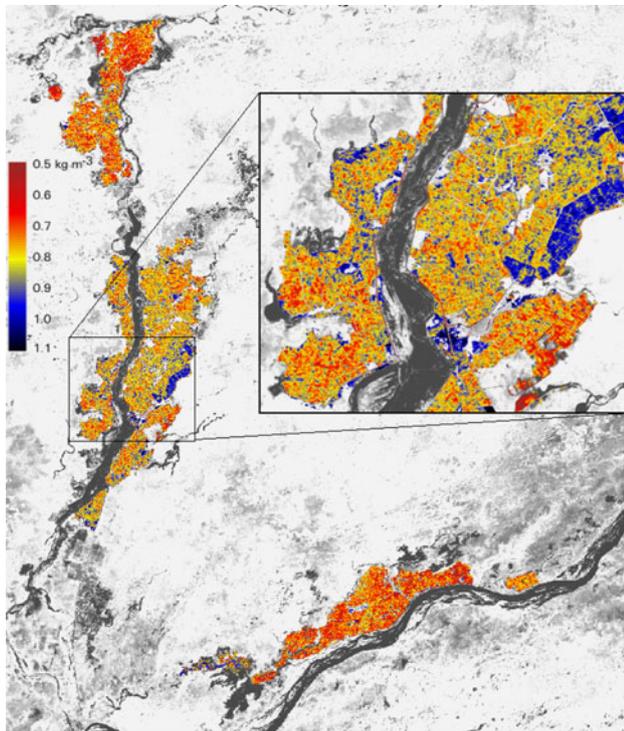


Fig. 6 The water productivity (kg m^{-3}) of rice in la Saison. The box shows the variation of water productivity around the city of Niono. The original resolution of the map is $30 \times 30 \text{ m}$

During the second rice season in the Saison Sèche chaude, precipitation is almost absent and irregular, and the availability of water for irrigation is low. However, in the zones of Niono, N'Debougou and Molodo, a strong increase in cropping intensity of rice can be found. In Macina and Kouroumari, this increase is much lower (Table 2). As indicated in the previous section, the central management decided to lower the *redevance* for farmers to irrigate crops during the second rice season. It can be concluded that farmers have responded positively to this policy change.

Productivity of water

The productivity of water (WP) is an irrigation performance indicator that provides information on the efficiency

of a system to produce crop yields for a given water consumption. In this study, the water consumption is defined as the amount of water that evaporates and transpires from an agricultural area. It does not refer to the amount of water that is applied or diverted to irrigate crops. No flow data have been used in this study. WP is calculated by dividing Landsat/SEBAL results of the estimated fresh rice yields in la Saison by the seasonal evapotranspiration. The map of WP (kg of rice fresh yield divided by m^3 of water evapotranspired) is depicted in Fig. 6.

According to official statistics, fresh rice yields between 1998 and 2002 amount to approximately 6 ton ha^{-1} (Aw and Diemer 2005). Wopereis et al. (1999) reported an average yield of 5.8 ton ha^{-1} for farmers with one rice crop, and 5.0 ton ha^{-1} for a double rice crop, based on a survey amongst 34 farmers in 1996. The SEBAL calculations show an average biomass production (Bio) of 15 ton ha^{-1} for rice in the Office du Niger. Assuming an average plant water content (θ_p) of 17.5% at harvest (Doorenbos and Kassam 1979), the harvest index (H_i) can be calculated back to 0.33 using the official statistics (see Eq. 1). This figure was used to convert the biomass production map into a fresh rice yield map. It is realised that by assuming H_i and θ_p constant, the estimate of spatial variability of rice production is reduced.

The average seasonal water consumption of rice is 754 mm with a standard deviation of 70 mm (see Table 3). This is relatively high when compared to the results of field measurements globally that lie between approximately 400 and 800 mm with some outliers (Zwart and Bastiaanssen 2004). Measurements of water balances in rice fields in the Office du Niger in the 1980s show even higher evapotranspiration rates of 720–910 mm in la Saison (Hendrickx et al. 1986). Water is abundant during la Saison, and fields are continuously over-supplied (Vandersypen et al. 2006), which is an explanation for the high water consumption.

The average WP in the 82,666 ha of rice cultivated in the Office du Niger during la Saison 2006 is 0.78 kg m^{-3} with a standard deviation (σ) of 0.12. This is low compared to the global range for water productivity of rice of $0.6\text{--}1.6 \text{ kg m}^{-3}$ that is based on the experimental results of thirteen sources worldwide (Zwart and Bastiaanssen 2004).

Table 3 Total area cultivated with rice in la Saison, and the averages (μ) of actual evapotranspiration, estimated fresh rice yields and water productivity for the Office du Niger as a whole, the five administrative zones and for the casiers located in the Niono zone

	Rice area (ha)	Actual evapotranspiration (mm)			Estimated rice yield (ton ha ⁻¹)			Productivity of water (kg m ⁻³)		
		μ	σ	c_v	μ	σ	c_v	μ	σ	c_v
Office du Niger	82,666	754	70	0.092	5.9	1.2	0.20	0.78	0.12	0.15
Zones										
Macina	22,109	753	71	0.095	5.5	1.1	0.20	0.72	0.12	0.17
Niono	22,359	759	65	0.086	6.4	1.1	0.17	0.83	0.11	0.13
N'Debougou	9,264	749	65	0.087	6.1	1.1	0.17	0.80	0.10	0.12
Molodo	10,306	786	63	0.080	6.5	1.0	0.16	0.81	0.10	0.13
Kouroumari	18,629	736	71	0.097	5.5	1.1	0.20	0.74	0.11	0.15
Casiers (zone of Niono)										
Grüber	2,659	751	65	0.086	6.2	1.0	0.16	0.82	0.09	0.11
Kolodougou	4,478	768	63	0.081	6.3	1.1	0.17	0.81	0.11	0.13
Retail I	4,577	749	60	0.081	6.4	0.9	0.14	0.84	0.09	0.10
Retail II	2,299	739	61	0.082	6.0	0.9	0.15	0.80	0.08	0.10
Retail IV	1,790	744	61	0.082	7.0	1.0	0.14	0.94	0.10	0.11

The standard deviation (σ) and the coefficient of variation (c_v) for each parameter are presented also

However, slightly lower values between 0.53 and 0.64 kg m⁻³ were measured in a rice-based system in Senegal (Raes et al. 1992), whereas in Nigeria, measured water productivities for rice ranged from 0.50 to 0.79 kg m⁻³ (Nwadukwe and Chude 1998).

The WP in the zones of Macina and Kouroumari is low at 0.72 and 0.74 kg m⁻³, respectively. The highest average WP is found in Niono (0.83 kg m⁻³) (see Table 3; Fig. 6). Although the water consumption in Macina is average compared to the entire system, the estimated rice yields are the lowest in the system (5.5 ton ha⁻¹ on average). It is uncertain what causes lower yields in this zone, but explanations can be sought in difference in growing conditions (e.g. soil types) or in irrigation management (e.g. the adequacy of water supply). In the zone of Kouroumari, the yields are also low at 5.5 ton ha⁻¹, but these coincide with the lowest seasonal water consumption (736 mm).

The lowest scale of analysis is the *casiers*. Only the five *casiers* of the zone of Niono were considered. WP in Grüber, Kolodougou, Retail I and Retail II depict little variation: average WP varies between 0.80 and 0.84 kg m⁻³. However, in Retail IV, the newest addition to the zone and located at the eastern boundary, the WP is significantly higher (0.94 kg m⁻³). The agricultural season there starts after the other four *casiers* are already supplied with water, which is related to historical water rights. Also, the average rice yield of 7.0 ton ha⁻¹ is significantly higher than in the other *casiers* where yields vary between 6.0 and 6.4 ton ha⁻¹. It was suggested by the managers of the *casiers* in Niono that soil fertility in Retail IV may be higher since this *casier* does not receive water and is not cultivated during the rest of the year.

Finally, it must be noted that the use of a fixed harvest index (H_i) implies a linear relationship between biomass production and rice grain yields. It is known, however, that external factors influence the number and weight of grains that a plant produces. A major determinant is the occurrence of crop water stress during the crop stages of flowering and grain filling (Hay 1995). Since crop water stress does not occur during la Saison, this is not expected to influence rice yields. However, under actual field conditions, the H_i will vary and this is not captured in the current rice yield estimates. Calibrating the biomass production map with field measured rice yields will improve the spatial estimates of rice yields from remote sensing imagery. Vandersypen et al. (2007) report that drainage problems at the time of harvest are widespread. Saturated fields induce lower rice quality and loss of production, which may be an explanation for the low H_i (0.33) that was found. This is, however, a variable that cannot be captured in the remote sensing calculations of rice yields, and that inhibits the calibration of remote sensing rice yields with field measurements.

Uniformity

The two indicators for uniformity are expressed by the coefficient of variation (c_v) of water consumption and the head–tail analysis of water consumption and rice yields. An analysis of both indicators was performed for the entire system, the five administrative zones and the *casiers* in the zone of Niono. Table 3 shows the results of the c_v at the different administrative levels. In Figs. 7, 8, 9 and 10, the results of the head–tail analysis are presented.

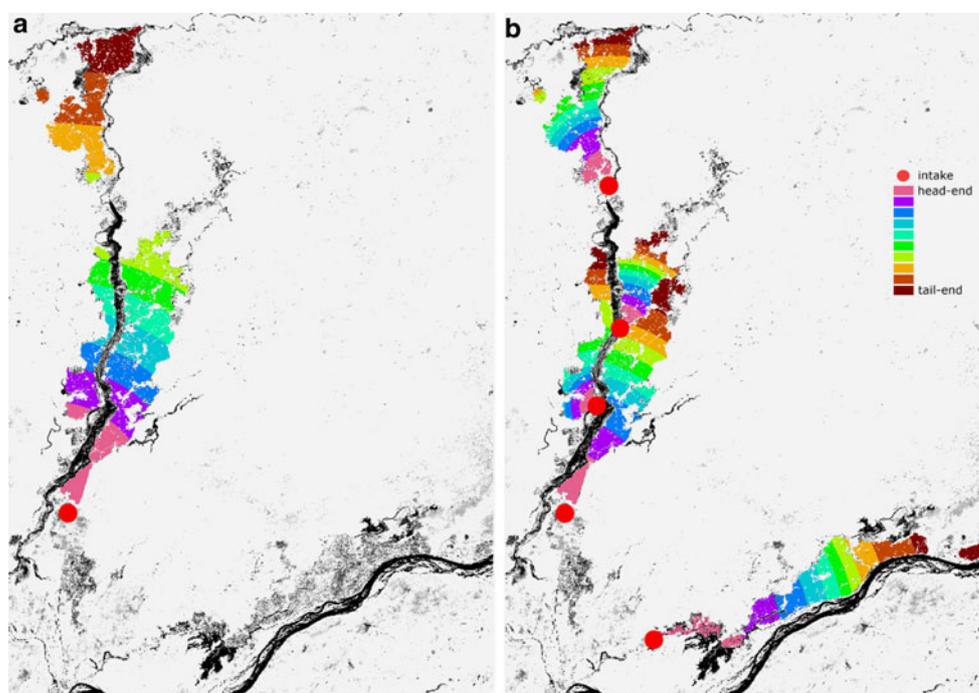
The c_v of water consumption in the Office du Niger equals 0.092 (Table 3) which implies that the water consumption is spatially heterogeneous during la Saison. As mentioned before, water is abundantly available during this season, and crop growth appears not to be hampered by water shortages (Vandersypen et al. 2006, 2009). The values for c_v found in the Office du Niger are similar to those measured in the Nile Delta in Egypt, which equalled 0.10 (Bastiaanssen 1997). In the five administrative zones, the c_v of water consumption varies from 0.080 in Molodo to 0.095 in Macina and 0.097 in Kouroumari. It can be noticed that the average estimated yields are the highest in Molodo (6.5 ton ha⁻¹) and the lowest in Macina and Kouroumari (both 5.5 ton ha⁻¹), hence a difference of 1.0 ton ha⁻¹. One explanation for the lower yields could therefore be a less homogeneous water distribution in these zones. Measurements of water deliveries to tertiary units between June and October 2004 varied from 8 to 30 m³ ha⁻¹ (Vandersypen et al. 2006), which confirms that a large difference in supply exists.

In order to further elaborate on the non-uniform patterns that were found, the head-/tail-end issues were evaluated using rice yield and water consumption patterns at the different administrative levels in the system. The division of the cropped area into ten equal areas measured from the intake are depicted in Figs. 7 and 9. The average water consumption (evapotranspiration) and estimated rice yields from head-end to tail-end are shown in Figs. 8 and 10.

If the Office du Niger is considered as one system, large differences were found in water consumption and

estimated yields between the beginning of the system and the end of the system. Average water consumption amounts to approximately 780 mm in the beginning of the system, but is 5% lower at the end of the system. However, estimated rice yields at the tail-end of the system are 18% lower with 5.4 ton ha⁻¹ compared to 6.5 ton ha⁻¹ at the head-end (see Fig. 8a). Consequently, the water productivity (WP) at the tail-end of the system is also lower. Although water is reported to be sufficiently available during la Saison, it can be concluded that rice yields are significantly lower towards the end of the system. Since water consumption is also lower at the tail-end (–5%), the lower yields may partially be attributed to irrigation water management. It remains uncertain, however, whether poor design and maintenance of structures and canals, or poor operation of the system, limit the possibilities of timely water supply to rice fields. Other factors may also explain the head–tail patterns such as deterioration of water quality towards the end of the system or waterlogging from poor drainage. It is reported by Valenza et al. (2000) that the groundwater levels towards the end of the system have risen to 2 m below the surface. Although both groundwater and irrigation water contain low concentrations of dissolved salts, these do accumulate at the soil surface due to evaporation of groundwater in combination with low permeability of soils and an absence of a proper functioning drainage system. The analysis of the system shows that there is significant scope for improvement in the productivity of the water resources. The construction of a well-functioning drainage network will be an intervention that

Fig. 7 Division of the cropped area during la Saison into ten equal areas (measured from the water intake) for the entire system except the zone of Macina (a) and for the five different zones including Macina (b)



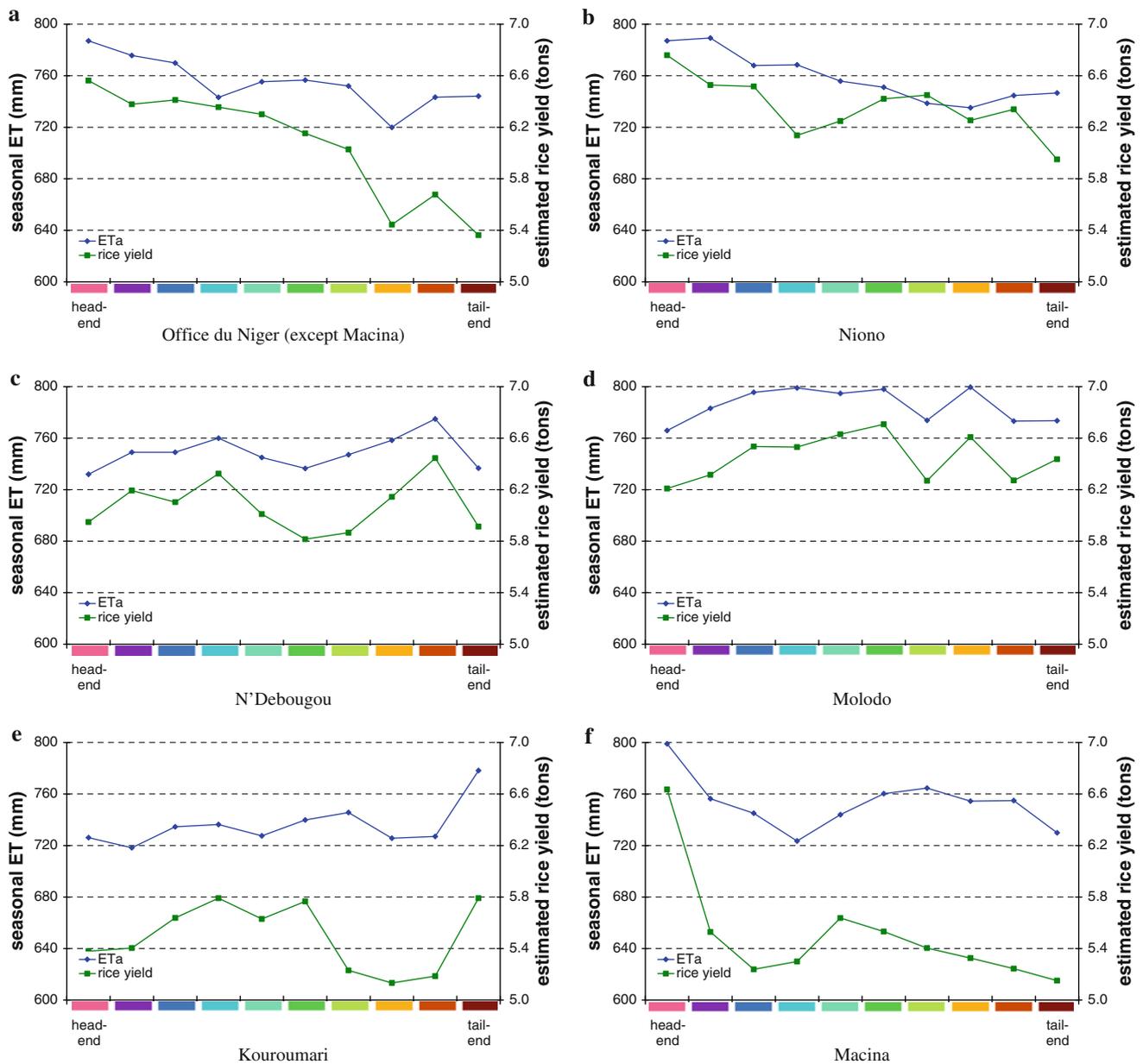


Fig. 8 Head–tail end patterns of water consumption from evapo-transpiration and estimated rice yields in la Saison. Shown are the average for the Office du Niger (a)—Macina is not included since it is

supplied directly from the Barrage de Markala—and the five administrative zones (b–f)

could lower salinity levels and improve crop yields and water productivity.

The uniformity of water consumption in the zone of Niono shows a similar pattern when compared to the entire system (Fig. 8b). Both rice yields (–12%) and water consumption (–5%) decrease towards the tail-end. Also in Macina, where rice yields are relatively low, the average yield and water consumption decrease towards the tail-end by –22 and –9%, respectively. In the other three zones (N'Debougou, Molodo and Kouroumari), both water consumption and rice yields remain at the same level in the

first 80% of the zone. An increase in rice yield and water consumption in the tail-end of N'Debougou and Kouroumari is shown, which may indicate waterlogging problems due to excess of drainage water.

At the level of the *casiers*, Grüber depicts a homogeneous water consumption and production (Fig. 10a). Rice yields in Retail IV are, at 7.0 ton ha⁻¹ on average, among the highest in the Office du Niger. Within the *casier*, the highest yields are found in the head-end of the casier (7.3 ton ha⁻¹), but also at the tail end, whereas the middle part of the casier produces less (6.4 ton ha⁻¹). A similar

Fig. 9 Division of the cropped area during la Saison into ten equal areas (measured from the water intake) for two casiers in the zone of Niono: Grüber (*left*) and Retail IV (*right*)

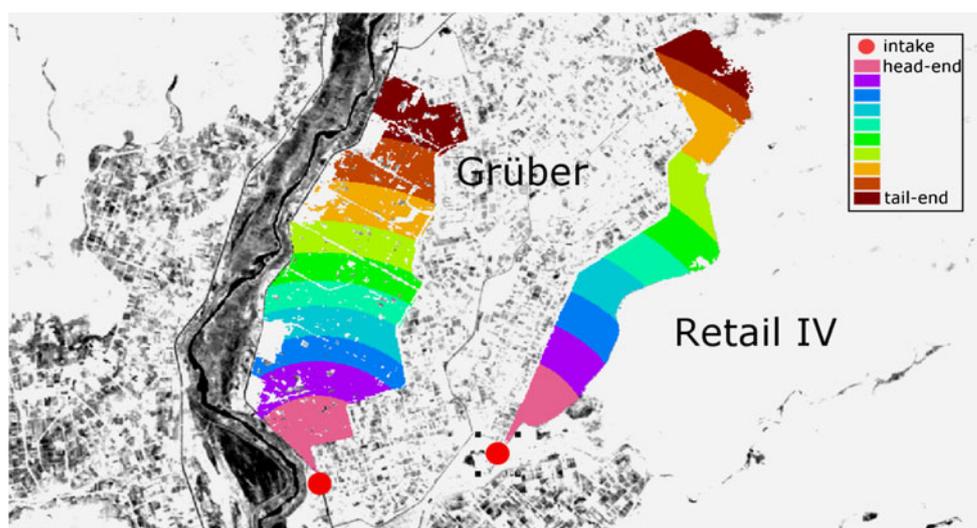
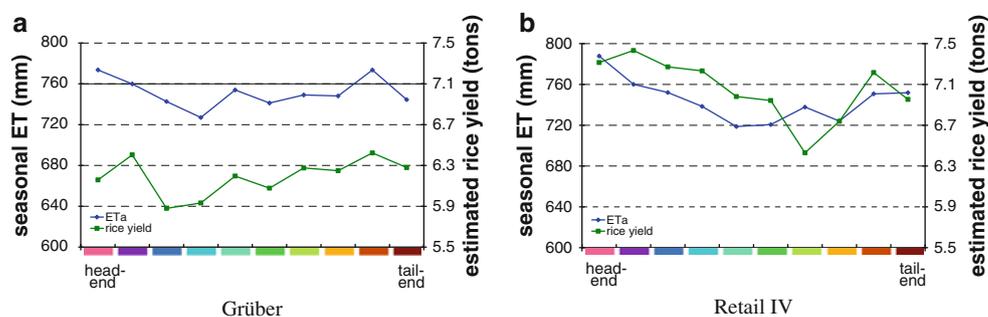


Fig. 10 Head–tail end patterns of water consumption from evapotranspiration and estimated rice yields in la Saison. Depicted are the casiers Grüber (a) and Retail IV (b)



pattern is found for the water consumption (Fig. 10b). According to the zone manager, sufficient water reaches the casier, but due to bad design of a structure located halfway, less water can reach the tertiary blocks thereafter. The increase in water consumption at the end of the casier is caused by excess drainage water, and moreover, the apparent increase in rice yields may be caused by the presence of weeds.

Discussions with irrigation managers

The results of this study were presented to the central management of the Office du Niger and to the directors of the zones and the managers of the casiers in the zone of Niono. The purpose was twofold: first of all, after outlining the methodology, the maps and graphs were interpreted and discussed using the field knowledge of the managers. This resulted in some new insights in the system. At casier level, causes of yield depression could be attributed to design failure of infrastructure. Examples included the wrong design and construction of a weir in casier Retail IV, and waterlogging due to the absence of a functioning drainage system. These issues and their causes were known, but it

was found that remote sensing as a diagnostic tool helps in defining the impact in areal and quantitative terms. At system level, the spatial variation of rice yields attracted interest, as well as the possibilities to map official (*casier*) and non-official (*hors-casier*) rice areas. The decreasing yields towards the end of the system could not be explained; suggestions included poorer water quality, waterlogging and lower soil fertility. It was agreed that a follow-up of this work should focus on explaining the differences in yield, water consumption and water productivity by spatially linking the results of this study to, for example, soil maps, piezometric levels, surface water flows or to the water quality information network. Only when the causes of poor performance in a specific area are understood can measure for improvement be designed. During the discussions, two limitations were encountered that need improvement, namely the influence of weeds in the results, and the use of a fixed harvest index. The latter was outlined before in the previous section. It was noted by the zone managers that the zone of Molodo is generally considered as the worst performing area. Drainage problems due to excess supply and poor maintenance or absence of drainage canals are common (Vandersypen et al. 2007; Aw and

Diemer 2005). Due to drainage problems, large sections are inundated and overgrown with weed (*Typha* sp.). However, from the remote sensing analysis, it was concluded that yields are among the highest (Table 3) and the water consumption and rice yields in this zones are homogeneously distributed (Fig. 8d). Similar effects can be witnessed in the tail-ends of the zones of N'Debougou (Fig. 8c) and Kouroumari (Fig. 8e), and in Retail IV (Fig. 10b). The separation of rice crops from weeds was not satisfactory in few specific, mainly, waterlogged areas. Research should therefore focus on improved methods to discriminate rice from non-rice areas, and on the calibration of rice yield with biomass production. In both cases, this will require the use of in situ measurements and observations.

The second purpose of the meetings was to explore the possibilities to use strategic remote sensing derived irrigation performance indicators for operational monitoring and evaluation of the system. Water deliveries during la Saison are reported to be much higher than the actual water demand from the rice crops, causing low efficiency of irrigation water application, water logging and water losses to drain areas. Moreover, due to poor drainage, rice yields in the fields are affected after harvested. Quantified spatial information from remote sensing data can assist irrigation managers to improve the operational performance of the system. By scheduling water supplies to match the water demands from evapotranspiration, the system irrigation efficiency can be increased and the productivity of water can be improved. Such an assessment would include quantifying and accounting for the unavoidable evaporation losses from the Falas (the abandoned river branches that are part from the irrigation system), and for the water demands from natural ecosystems and non-official rice cultivation that depend on water diversions from the Niger. Remote sensing indicators may support operation and scheduling, as well as evaluating the seasonal performance, thus aiming at the improvement of the operational and strategic performance of the system. It was mentioned, however, that the current set of remote sensing performance indicators should be updated with indicators that use measurements of precipitation and irrigation water diversions to assess the efficiency of water supplies at various levels within the system. Examples of such indicators that can be assessed spatially are the irrigation efficiency, the depleted fraction and the relative water supply. Incorporation of these in operational systems demands changes in the organisational system and training of staff to interpret the images and the performance indicators, and to provide water scheduling advice. However, implementation of remote sensing-based diagnostic and strategic performance analysis over a shorter term was considered to be feasible.

Costs

Considering the maximally irrigated area of 82,666 ha during la Saison, the costs per hectare of remote sensing-based analysis of productivity and water use were only US\$ 0.30. In a similar study of the irrigation performance in a 100,000 ha irrigation scheme in India, the costs per hectare were reported as US\$ 0.10 (Thiruvengadachari and Sakthivadivel 1997). However, since a breakdown of costs was not specified, it could not be determined how much time was spent on the study and at what rates these were charged.

Conclusions

Strategic and diagnostic irrigation performance indicators, entirely based on remote sensing derived data, were applied to assess the cropping intensity, the productivity of water and the uniformity of water consumption in the Office du Niger. Perceptions of irrigation performance by managers of the zones and casiers were confirmed, whereas at higher level, remote sensing data provided new insights on patterns of rice yields and water productivity. The low average water productivity throughout the system (0.78 kg m^{-3}), the high coefficient of variation for yields (0.20) and decreasing rice yields towards the tail-end of the system (-18%) show that there is scope for improvement. At specific locations, low yields could be attributed to failing irrigation and drainage infrastructure, whereas for other areas, it was found that more research is required to find the underlying reasons for low performance. The change in the water pricing policy during the second rice season was confirmed to positively affect the cropping intensity in recent years.

However, discussions of the current results identified two topics that need attention. The first point concerns the rice map that was used during this study. Weed crops (*Typha* sp.) that are mainly present in inundated rice fields with poor drainage were not distinguished from rice in Molodo, and in the tail-ends in the zones of Macina and N'Debougou. Estimated rice yields were therefore higher than one would expect in these areas. The second limitation of the current methodology is the assumed linear relationship between biomass production and rice yields through a constant value for the harvest index (H_i). Research should focus on the calibration of the biomass production maps with field measured yields, which will spatially improve the results.

During discussions of the results, the managers of the Office du Niger as well as donor agencies showed great interest in the results and the possibilities that remote sensing offer. The diagnostic performance assessment

supports the process to define priority areas for rehabilitation, whereas a *comparative* performance assessment can be applied to set benchmark standards for the performance, to detect processes in the system that lead to higher performance and to quantify the impact of an intervention. It was acknowledged, however, that remote sensing derived indicators only partially cover the data need for a full irrigation performance analysis in the Office du Niger.

Acknowledgments The authors wish to thank the staff of the Office du Niger for their lively discussions and their constructive feedback which was used to improve the analysis of the results. This study was financially supported by the Programme National d'Infrastructures Rurales (PNIR). Souleymane Sidibe of the Office du Niger in Ségou, and Pieter Raijmakers and Michiel de Smet of Euroconsult Mott MacDonald are kindly acknowledged for facilitating field visits and providing support. Klaartje Vandersypen's detailed and constructive comments on the original manuscript were very much appreciated.

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