Irrigation performance assessment using remote-sensing data: A case study of the Office du Niger, Mali

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Abstract

The irrigation performance of the Office du Niger in Mali, a large-scale rice-based irrigation scheme, was analyzed 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 organizational levels of the system. The SEBAL model was applied to high-resolution Landsat images to calculate rice production and water consumption spatially. These maps were used to analyze the productivity of water, the uniformity of water consumption including head- and tail-ender 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 Normalized Difference Vegetation Index. The results were discussed and interpreted with the irrigation managers of the Office du Niger. The analysis provided new insights into the performance of the system, such as existing head–tail patterns in water consumption and rice yields.

Introduction

In the past 10 years, the possibilities to use spatial remote-sensing data operationally have been investigated. New remote-sensing models and algorithms have been developed enabling spatial derivation of hydrological information (e.g. soil moisture, potential and actual evapotranspiration, precipitation) and agronomic information (e.g. land use, crop type, biomass production, crop water and nitrogen stress). In parallel, more satellites have been launched, offering a wider range of options in terms of spatial and temporal resolutions. 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. Improvements in available remote-sensing data offer the possibility to get information in data-scarce regions. Moreover, major advantages of remote-sensing-derived data over field-measured data are that they are objective and collected systematically and system-wide. Analysis can also be performed at different scales (Bastiaanssen *et al.*, 2000).

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 at high resolution, focusing 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 overall system performance. The Office du Niger, a large-scale, rice-based irrigation system of 80 000 ha along the Niger River in Mali, was used as a study area (Fig. 1).

Materials and methods

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

- Cropping intensity from a long-term Normalized Difference Vegetation Index (NDVI) time-series (July 1998 to June 2008);
- Productivity of water (WP), defined as estimated rice yield divided by water consumption from evapotranspiration;
- Uniformity, the coefficient of variation (CV) of water consumption by evapotranspiration to evaluate the uniformity of water consumption; and
- Head–tail performance indicator, for assessing the spatial pattern of water consumption, rice yields and water productivity among irrigators in head and tail reaches.

The SEBAL model was applied to 12 high-resolution satellite images taken by the Landsat sensor during the 2006/07 irrigation season (Fig. 2) to obtain maps of seasonal actual evapotranspiration and biomass production for the main rice season 2006 (main seasonAugust to December during the rainy season) and the second smaller rice season 2007 (March to June). These were used to analyze the uniformity of water consumption and the productivity of water at different spatial scales. Figure 3 shows the different inputs needed for the SEBAL algorithm. The details of the SEBAL algorithm are described in Bastiaanssen *et al.* (1998), Bastiaanssen and Ali (2003) and Zwart and Bastiaanssen (2007).

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

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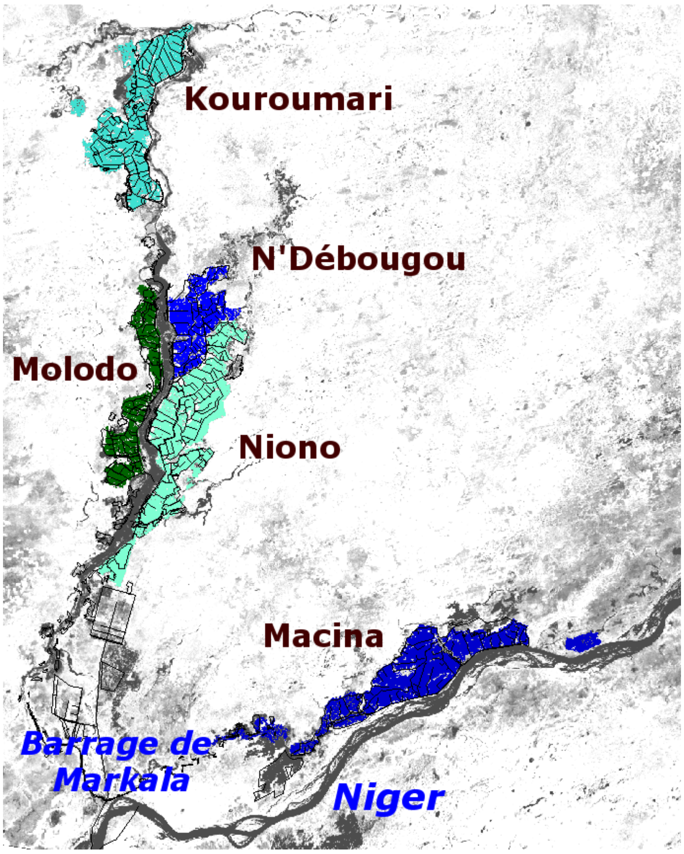

Figure 1. Layout of the Office du Niger, Mali. The five administrative zones are indicated, as well as the Barrage de Markala in the southwest corner and the Niger River running south of the system.

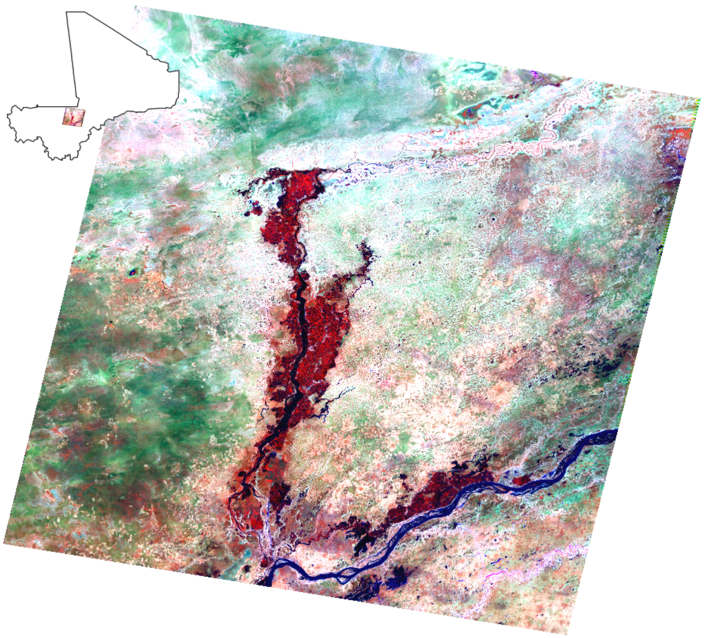

Figure 2. Location of the Office du Niger in Mali on a Landsat7 image acquired on 5 October 2006. The image is depicted in the false-color band combination 4–5–3. Red indicates green vegetation. The Niger River is located in the southeastern (bottom right) part of the area shown.

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 in the paper.

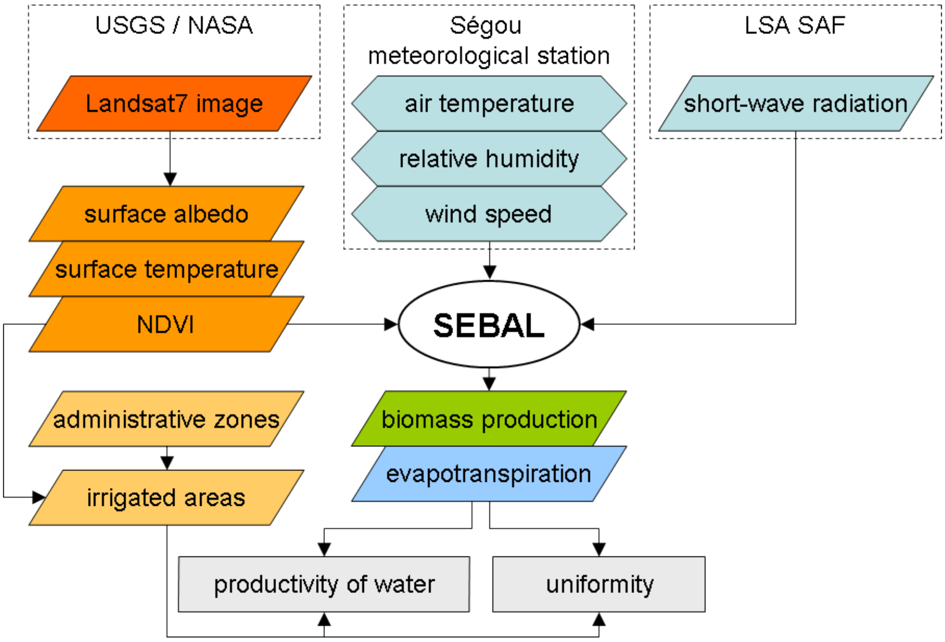

Figure 3. Visual representation of the SEBAL inputs that are required to calculate biomass production and actual evapotranspiration from Landsat images, and then the performance indicators.

Results

Only the results for the water productivity, uniformity and head–tail performance indicators are discussed in this paper.

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. Water productivity is calculated by dividing Landsat/SEBAL results of the estimated fresh rice yields in main season by the seasonal evapotranspiration. The map of WP (kg of rice fresh yield divided by m^3 of water evapotranspired) is presented (Fig. 4).

According to official statistics, fresh rice yields between 1998 and 2002 were approximately 6 tonnes/ha (Aw and Diemer, 2005). Wopereis *et al.* (1999) report an average yield of 5.8 t/ha for farmers with one rice crop, and 5.0 t/ha per crop for farmers with a double rice crop, from a survey of 34 farmers in 1996. The SEBAL calculations show an average biomass production (*Bio*) of 15 t/ha 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. This figure was used to convert the biomass production map into a fresh rice yield map. It is realized 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 was 754 mm with a standard deviation of 70 mm (see Table 1). This is relatively high compared to the results of field measurements globally that lie between about 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 main season (Hendrickx *et al.*, 1986). Water is abundant during main season and fields are continuously over-supplied (Vandersypen *et al.*, 2006), which explains the high water consumption.

The average WP in the 82 666 ha of rice cultivated in the Office du Niger during main season 2006 was 0.78 kg/m^3. This is low compared to the global range for water productivity of rice of 0.6–1.6 kg/m^3 that is based on the experimental results of 13 sources worldwide (Zwart and Bastiaanssen, 2004). However, slightly lower values between 0.53–0.64 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).

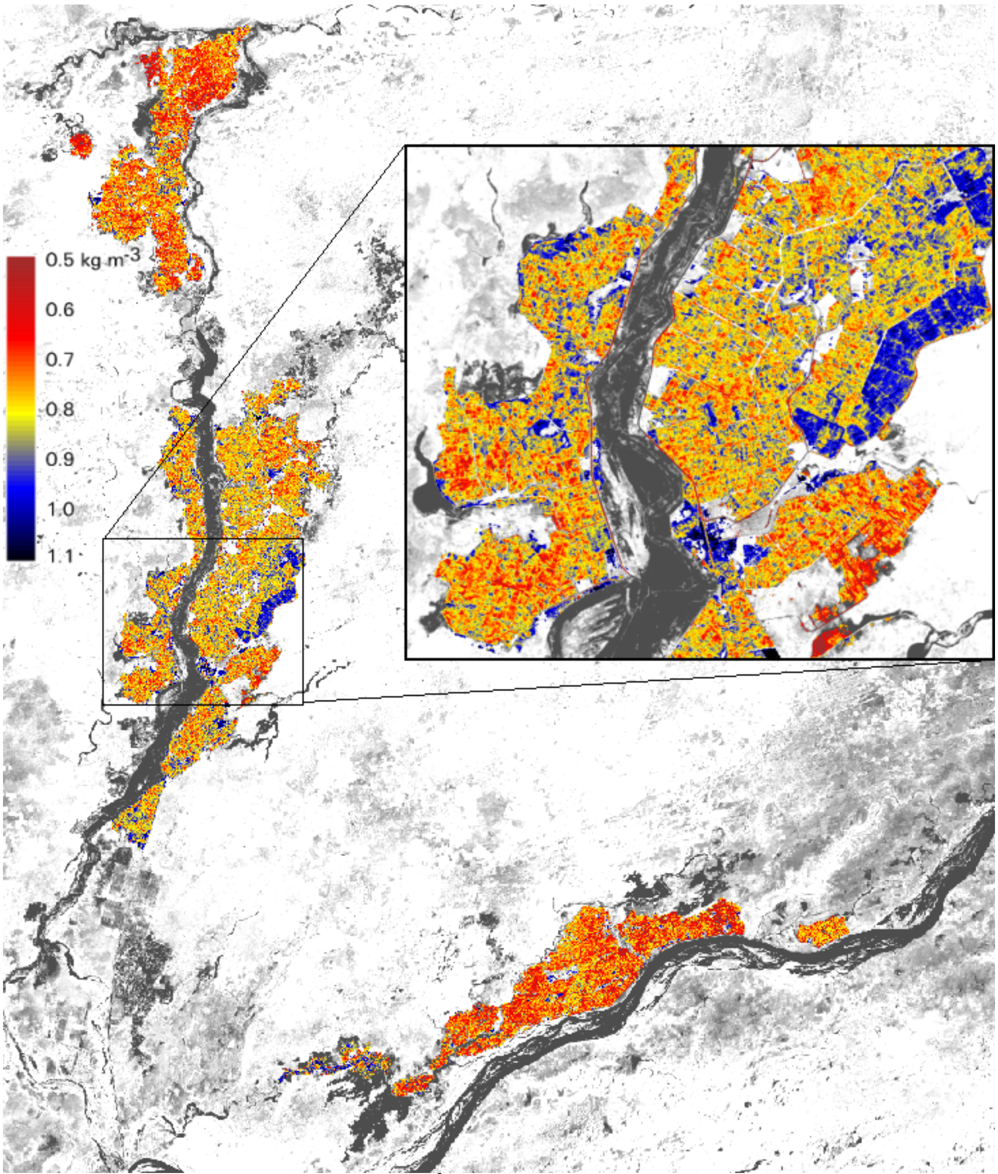

Figure 4. Water productivity (kg/m^3) of rice in main season. The box shows the variation of water productivity around the city of Niono. Spatial resolution (pixel size): 30 × 30 m.

The WP in the zones of Macina and Kouroumari was low (0.72 and 0.74 kg/m^3, respectively). The highest average WP was in Niono (0.83 kg/m^3) (see Table 1 and Fig. 4). Although the water consumption in Macina was average compared to the entire system, the estimated rice yields were the lowest in the system (average 5.5 t/ha). It is uncertain what causes lower yields in this zone, but explanations can be sought in differences 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 were also low (5.5 t/ha), but these coincided with the lowest seasonal water consumption (736 mm). A similar analysis can be done at the *casier* scale, which would allow comparison of water productivity per tertiary unit, identification of the problem area and prioritization of the tertiary units for an upcoming rehabilitation project.

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 water stress during flowering and grain filling (Hay, 1995). Since crop water stress does not occur during main season, this is not expected to influence rice yields. However, under actual field conditions H_i will vary and this is not captured in the current

Table 1. Total area cultivated with rice in main season, 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 the *casiers* located in Niono zone. The standard deviation (σ) and the coefficient of variation (CV) for each parameter are also presented

Unit	Name	Rice area (ha)	Actual evapotranspiration (mm)			Estimated rice yield (t/ha)			Productivity of water (kg/m^3)		
			μ	σ	CV	μ	σ	CV	μ	σ	CV
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	Grüber	2 659	751	65	0.086	6.2	1.0	0.16	0.82	0.09	0.11
(zone of	Kolodougou	4 478	768	63	0.081	6.3	1.1	0.17	0.81	0.11	0.13
Niono)	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

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 harvest time 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 (CV) 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. The results of the CV at the different administrative levels are shown (Table 1), as are the results of the head–tail analysis (Fig. 5–8).

The CV of water consumption in the Office du Niger was 0.092 (Table 1), which implies that the water consumption is spatially heterogeneous during main season. As mentioned above, 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 CV found in the Office du Niger are similar to those measured in the Nile Delta in Egypt (0.10; Bastiaanssen, 1997). In the five administrative zones, the CV of water consumption varied from 0.080 in Molodo to 0.095 in Macina and 0.097 in Kouroumari. The average estimated yields were highest in Molodo (6.5 t/ha) and lowest in Macina and Kouroumari (both 5.5 t/ha) — a difference of 1.0 t/ha. 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 m^3/ha (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- and tail-ender 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 10 equal areas measured from the intake is depicted (Fig. 5 and 7). The average water consumption (evapotranspiration) and estimated rice yields from head-end to tail-end are shown (Fig. 6 and 8).

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 amounted to approximately 780 mm in the beginning of the system, but was 5% lower at the end of the system. However, estimated rice yields at the tail-end of the system were 18% lower (5.4 cf. 6.5 t/ha) (see **Figure** 6). Consequently, the WP at the tail-end of the system was also lower. Although water is reported to be sufficiently available during main season, 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, the lower yields may partly 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 toward the end of the system or waterlogging from poor drainage. 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 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. 6b). Both rice yields (–12%) and water consumption (–5%) decreased toward the tail-end. Also in Macina, where rice yields were relatively low, the average yield and water consumption decreased toward the tail-end(–22% and –9%, respectively). In the other three zones (N'Debougou, Molodo and Kouroumari), both water consumption and rice yields remained at the same level in the first 80% of each zone. There was an increase in rice yield and water consumption in the tail-end of both N'Debougou and Kouroumari, which may indicate waterlogging problems due to excess of drainage water.

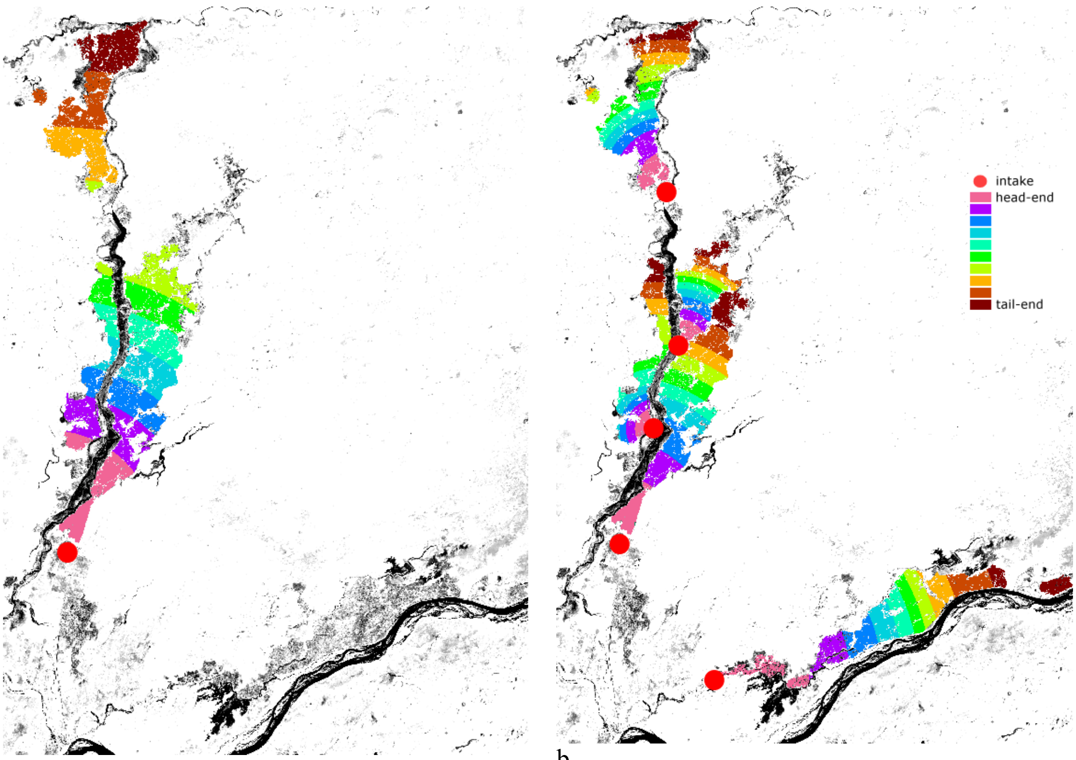

Figure 5. Division of the cropped area during main season into 10 equal areas (measured from the water intake) for the entire system except the zone of Macina (a) and for each of the five zones including Macina (b).

At the level of the *casiers*, Grüber had a homogeneous water consumption and production (Fig. 8a). Rice yields in Retail IV were among the highest in the Office du Niger (average 7.0 t/ha). Within this *casier*, the highest yields were at the head-end (7.3 t/ha) and at the tail-end, but the middle part of the *casier* produced less (6.4 t/ha). A similar pattern was found for water consumption (Fig. 8b). 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; 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, to the directors of the zones, and the managers of the *casiers* in Niono. The purpose was two-fold: first, 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 into the system. At *casier* level, causes of yield depression could be attributed to infrastructure design failure. Examples included the wrong design and construction of a weir in Retail IV, and waterlogging due to the absence of a functioning drainage system. These issues and their causes were known, but using remote sensing as a diagnostic tool helped in defining the impact in area 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 toward 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 measures 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 is outlined under 'Productivity of water' above. Zone managers noted that the zone of Molodo is generally considered 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 weeds (*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 homogenously distributed (Fig. 6d). Similar effects can be seen in

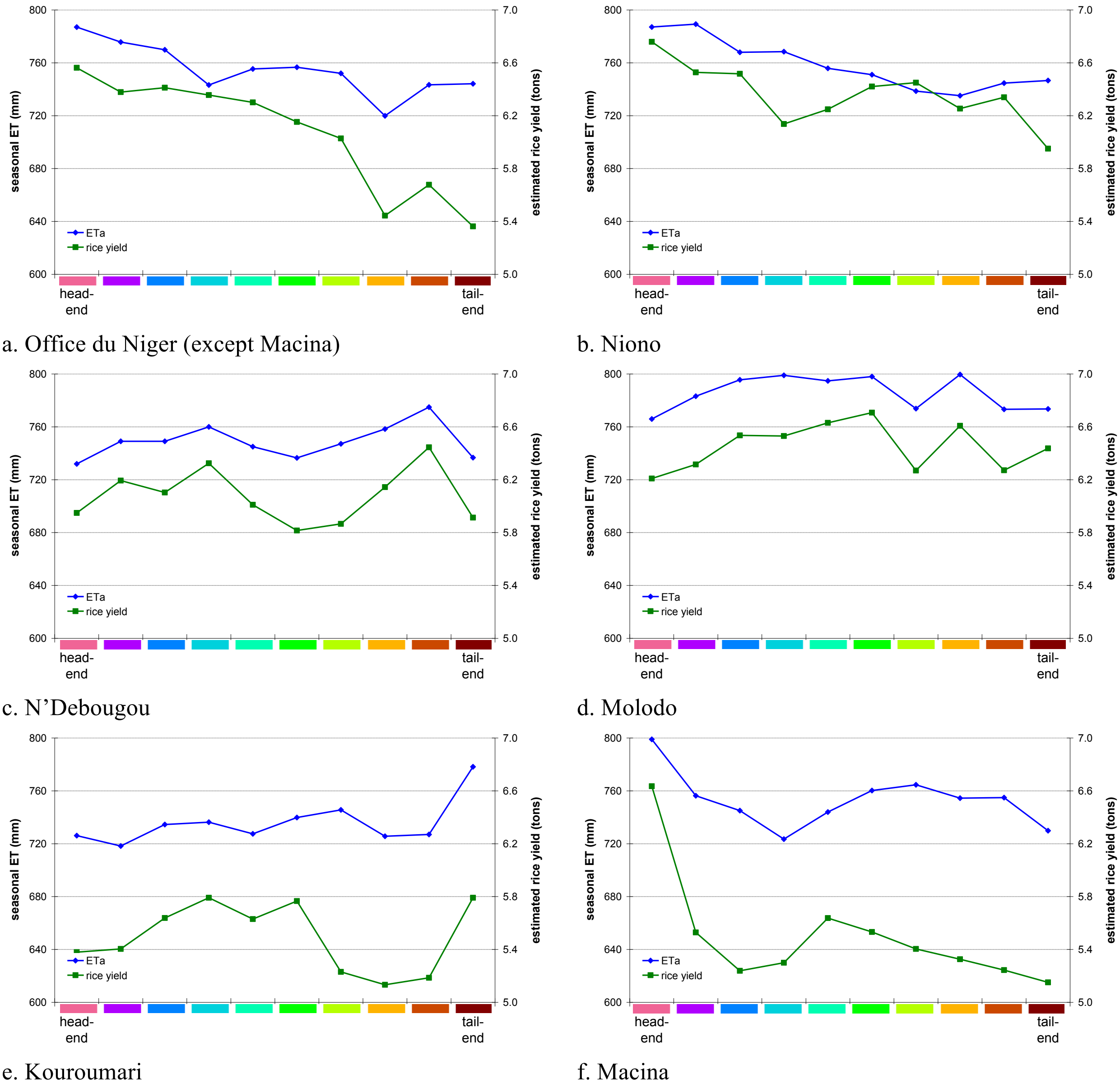

Figure 6. Head–tail end patterns of water consumption from evapotranspiration and estimated rice yields in main season: (a) average for the Office du Niger excluding Macina (which is supplied directly from the Barrage de Markala); and (b–f) the five administrative zones.

the tail-ends of the zones of N'Debougou (Fig. 6c) and Kouroumari (Fig. 6e), and in Retail IV (Fig. 8b). The separation of rice crops from weeds was not satisfactory in a 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 irrigation performance indicators derived from remote-sensing data for operational monitoring and evaluation of the system. Water deliveries during main season are reported to be much higher than the actual water demand of the rice crops, causing low efficiency of irrigation water application, waterlogging and water losses to drain areas. 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 of the irrigation system), and for the water demands of natural ecosystems and unofficial rice cultivation that depend on water diversions from the Niger River. Remote-sensing indicators may support operation and scheduling, as well as evaluation of seasonal performance, and

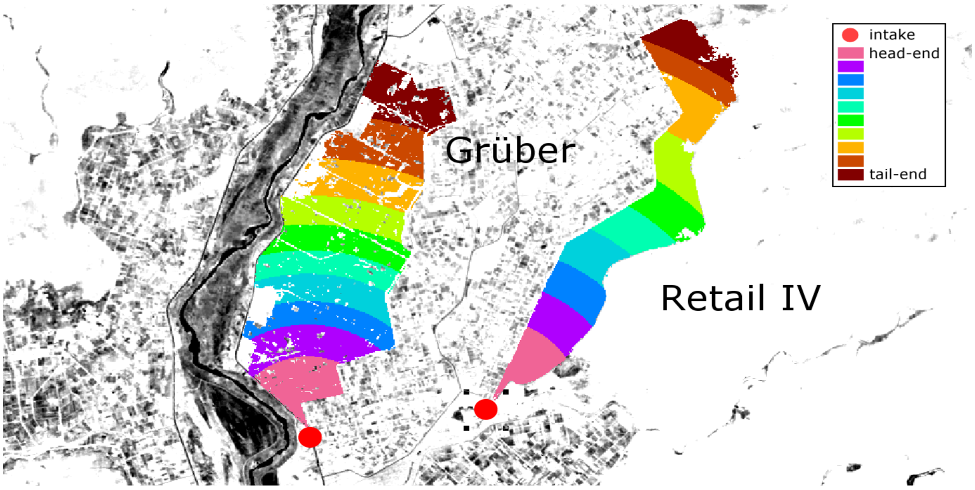

Figure 7. Division of the cropped area during main season into 10 equal areas (measured from the water intake) for two *casiers* in the zone of Niono: Grüber (left) and Retail IV (right).

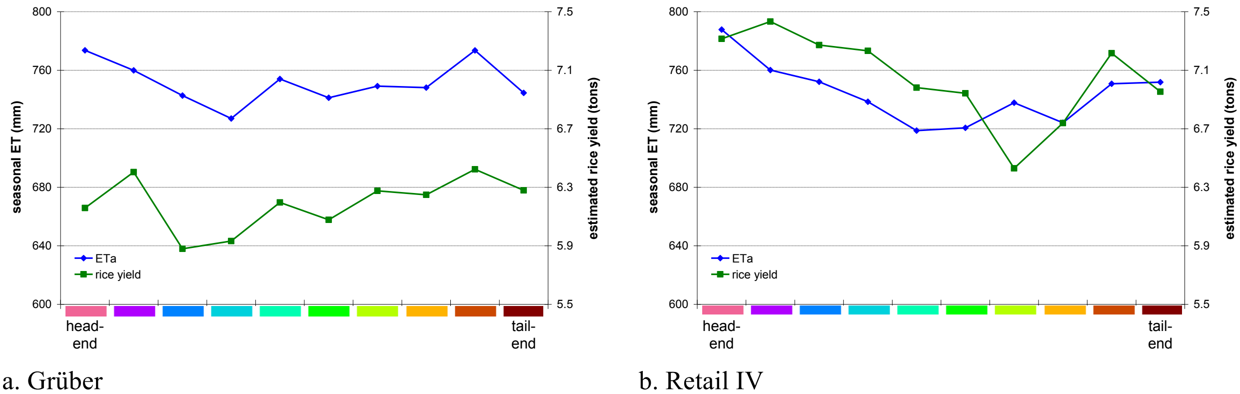

Figure 8. Head–tail end patterns of water consumption from evapotranspiration and estimated rice yields in main season: *casiers* Grüber (a) and Retail IV (b).

thereby support 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 into operational systems demands changes in the organizational system and training of staff to interpret the images and 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 main season, 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.

Discussion

Strategic and diagnostic irrigation performance indicators, based entirely on remote-sensing-derived data, were applied to assess the cropping intensity, productivity of water, and 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 toward 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 more research is required to find the underlying reasons for poor performance. The change in the water pricing policy during the second rice season (implemented in 2001/02) was confirmed to positively affect the cropping intensity.

Discussions of the results identified two topics that need attention, however. The first point concerns the rice map that was used during this study. Weeds (*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 expected in these areas. The second limitation of the current methodology is the assumed linear relationship between biomass production and rice yields through the use of a constant value for 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 discussion 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 offers. 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 needs for a full irrigation performance analysis in the Office du Niger.

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