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Agricultural land investments and water management in the Office du Niger, Mali: options for improved water pricing

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ABSTRACT
Large-scale agricultural land investments in Africa are often considered solely from the land perspective. Yet land, water and other natural resources are closely interlinked in agricultural production and in sustaining rural livelihoods. Such investments involving irrigation will potentially have implications for water availability and utilization by other users, making it imperative to regard water as an economic rather than a free good. Focusing on a vast irrigable area in Mali with recent large-scale investments, a bio-economic model was used to demonstrate that an improved water valuation system is needed to balance different water users' needs while ensuring adequate environmental flow.

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Introduction

The large-scale investments in agricultural land (LSIALs) in Africa that have featured prominently in public discourse over the last few years have essentially focused on land alone (Kizito, Williams, McCartney, & Erkossa, 2012; Woodhouse, 2012). However, land and water are closely interlinked resources (Williams, Gyampoh, Kizito, & Namara, 2012). For crops such as rice and sugar cane, irrigation is needed to avoid crop failure and to increase productivity (de Fraiture & Wichelns, 2010). Water and land sustain ecosystem services – provisioning, regulating, supporting and cultural – that are important to rural populations, who rely on them for livelihood in several African countries (Cotula & Vermeulen, 2011; Kizito et al., 2012; OCDE, 2002). The International Water Management Institute, through the Challenge Programme on Water and Food and the more recent CGIAR Research Programme on Water, Land and Ecosystems, has always underscored the critical importance of sustainable land and water management in addressing the challenges affecting food production and the underlying natural resources and ecosystems in Africa (IWMI, 2014).

Yet, water is the ignored dimension in large-scale land deals. It is hardly explicitly included in many land acquisition contracts, and when included, it is inadequately valued.[1] The water rights of smallholder farmers and the potential impacts of large-scale land use, occasioned by the agricultural production activities of investors, are other dimensions that are not adequately considered when lands are leased out (Cotula, 2011). Poor management of water in large-scale irrigation

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schemes can have negative consequences, including wasteful and inefficient water use, early degradation of infrastructure and environmental damage (Deininger, 2011a, 2011b; Djiré, Kéita, & Diawara, 2012; Sindayigaya, 2012; German, Schoneveld, & Mwangi, 2013). Nonetheless, it is equally recognized that large-scale investments (foreign or domestic) in agricultural land can make positive contributions to the economy of many African countries that are still largely dependent on agriculture (Collier, 2008; Cotula, Vermeulen, Leonard, & Keeley, 2009; Lavers, 2012). Through the infusion of capital, new technology and knowledge, such investments can increase agricultural production and improve national food security, while contributing to government tax revenues and water supply cost recovery. Therefore, an appropriate water pricing system that recognizes the economic value of water is crucial to obtain full benefits from these investments, while protecting the livelihood of other users and the environment. This article elaborates an alternative to the current system of irrigation water pricing in the study area of the Office du Niger (ON) in Mali.

The ON covers a large irrigable area of over one million hectares in the inner delta of the Niger River, stretching from Ségou in the south to areas of Mopti in the north. Office du Niger is also the name of the semi-autonomous agency in charge of the development of the area. The Malian government has proactively promoted a policy of opening up land in the ON area to investors, with the intention of making the country the ‘food basket’ of the West African region (Brondeau, 2011; Kuper & Tonneau, 2002; Republique du Mali, 2013). Abundant water resources and favourable agro-ecological conditions clearly appear to be some of the major driving forces behind private large-scale investment schemes in the area (Woodhouse, 2012). Water use for irrigation is viewed as a way to substantially increase crop yields and boost profits. More than 200,000 ha of land is currently leased and intended for growing highly water-demanding crops such as rice and sugar cane. Consequently, a significant share of the country’s water resources may be used in these investments, as suggested by an analysis of similar LSIALs in Ethiopia (Bossio et al., 2012).

Considering growing future demands for water, due to increased urbanization and industrial-sector growth, and the reduced rainfall suggested by climate change projections (ODI & CDKN, 2014), the inadequacy and limitations of the water management system currently in place in the ON are likely to quickly surface. The present water management system relies on a flat rate per hectare pricing. Economic theory and empirical analysis suggest that this pricing system is ineffective, in the sense that it does not encourage water conservation because it does not send the right signals to water users to inform them of the relative scarcity of the resource (Johansson, 2000; Johansson, Tsur, Toe, Doukkali, & Dinar, 2002; Griffin, 2006). Therefore, the land investor is unable to properly assess the marginal value of the water used in agricultural production. An alternative approach explored in this article, based on a volumetric water pricing, should help to efficiently allocate water in the face of scarcity and to recover the costs of water supply while promoting environmental protection (Rogers, De Silva, & Bhatia, 2002). Although the flat rate per area pricing implemented in the ON has been widely criticized (Brondeau, 2011; Hertzog, Adamczewski, Molle, Poussin, & Jamin, 2012), options for implementing a volumetric water pricing system have not been investigated. This article is intended to address this neglected potential and thereby fill a gap.

The article analyzes different existing and possible future agricultural land investment scenarios in the ON and shows how a volumetric water pricing system leads to a more efficient valuation of agricultural water. A uniform pricing system is considered as it is the simplest volumetric pricing model and may be more adapted for the ON presently using a per area flat rate. A bio-economic model, combining bio-physical and economic considerations, is developed to simulate the likely impacts of LSIALs under two alternative water pricing systems: the current flat rate per hectare pricing and a volumetric pricing. A comparative analysis of the effects of the different pricing systems is undertaken in terms of efficiency of water allocation, environmental flow requirements and cost recovery. The article provides evidence for the merits of volumetric water pricing while addressing some of the possible political-economy implications of adopting such a pricing system.

The article is organized as follows. The next section describes the methodological framework used. The subsequent section presents the results and discusses how volumetric water pricing can help address water management problems in the ON. The concluding section draws out the policy implications of adopting a volumetric water pricing system.

Methodological framework

Description of the study area

The analysis focuses on the ON area. Created in 1932 by the French colonial administration, the Office du Niger refers to both the area of the inner delta of the Niger River in Mali (about 1,000,000 ha)[2] and the semi-autonomous government agency in charge of the management and development of the land and water resources in the area (INSTAT, 2012). Water from the Niger River is diverted into a system of canals at the Markala Dam and used for irrigation in smallholder plots as well as large-scale farms (Coulibaly, Béliéres and Koné, 2006). The main crops presently grown are rice and sugar cane, although the area was intended for cotton production for the French textile industry. The ON has experienced major difficulties over the years and went through several reforms in the 1990s, resulting in the cutting back of the monopoly power of the agency over agricultural production and marketing of cereals (Hertzog et al., 2012). The ON is now limited to the management of land and water and provision of agricultural advisory services. All the production activities that it used to undertake have now been privatized. The ON is not directly mandated to handle environmental protection but may intervene if its water management system is affected by environmental problems (especially aquatic weeds). The agency uses a flat rate per area water pricing system called *redevance eau* (water fee) (Kéita, Belieres, & Sidibe, 2002). It is mandated to cover only the management, maintenance and operation costs.

The choice of the ON area for this analysis was motivated by its strategic importance for the country's socio-economic development (Djiré et al., 2012), its attractiveness to foreign and domestic investors and its rich ecological profile (wetlands, aquatic animals and rich biodiversity). The climate is of Sahelian semi-arid type, with annual average rainfall ranging between 600 and 750 mm. Annual mean temperature is 28 °C, and the annual mean maximum temperature is 35 °C

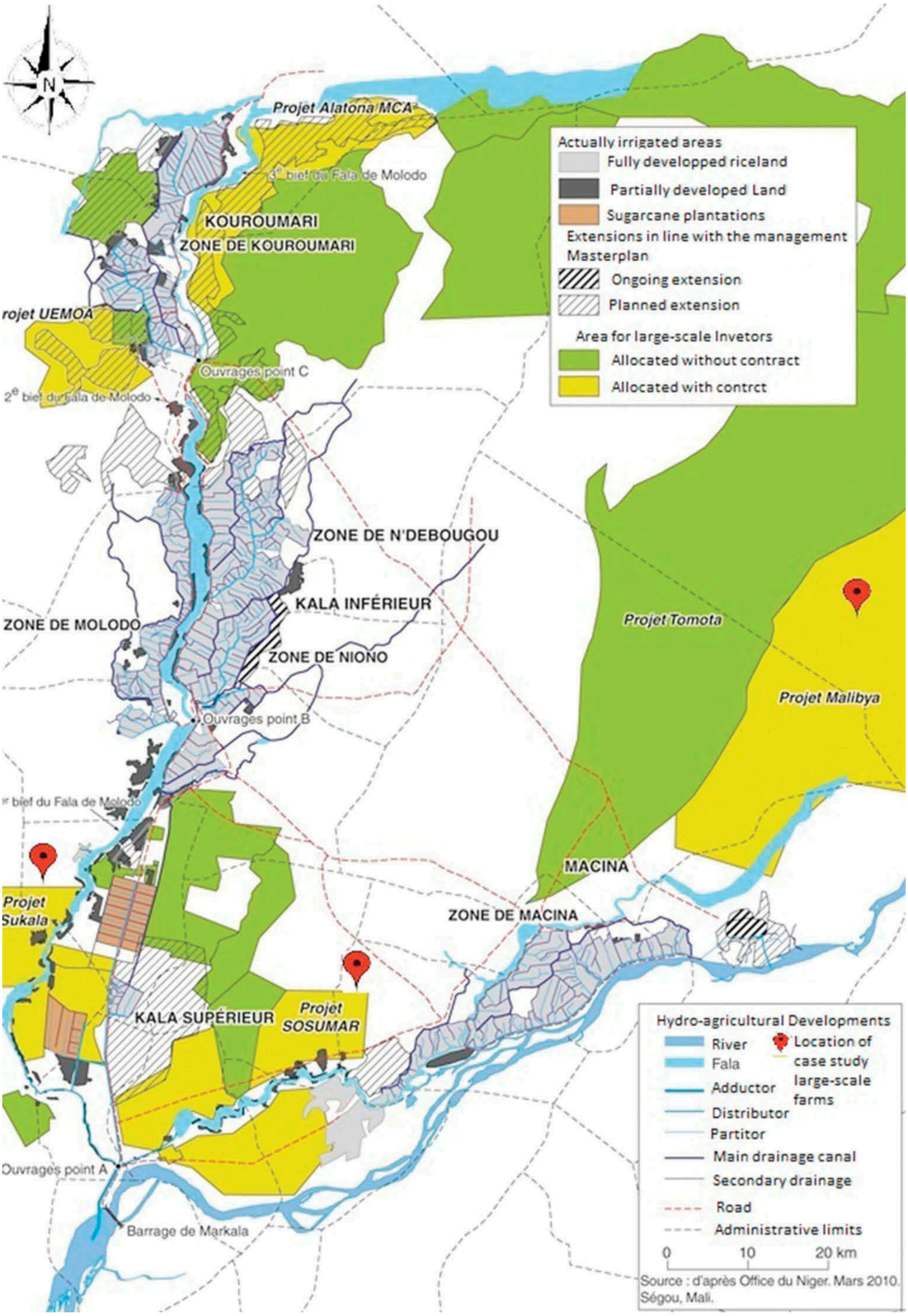
(CLIMWAT, 2011). The soils are predominantly arenosols featuring on deep aeolian alluvial sands with a sandy loam texture (Kizito et al., 2012). There are two major growing seasons. The ‘wet season’, from June to September, is the main agricultural season. The second agricultural season (‘dry season’) starts in October. Most local people are poor subsistence farmers, heavily reliant on natural resources and vulnerable to the vagaries of the climate (Michigan State University, 2011). Figure 1 shows the location of three major schemes in the ON.

Model description

A bio-economic model that combines a crop growth model with a farm-level micro-economic model is developed. The crop growth model indicates how much yield is obtained for a given amount of water, while the economic model shows how much profit is obtained for a particular yield level and water price. This modelling approach, linking an empirical economic model and bio-physical models, has been used in a number of studies (Reynaud, 2009; Sidibé, Terreaux, Tidball, & Reynaud, 2012; Stoorvogel, Antle, Crissman, & Bowen, 2004). The advantage of such an integrated assessment approach (compared to a classic econometric approach) is that it creates a tool that is able to simulate behaviours outside the range of the observed domain and account for non-linearities (Antles and Capalbo, 2001). It can be used to simulate the impact of policy on different relevant variables (water use, production, incomes, etc.) both within and outside the range of observed data in a way that is consistent with economic theory and with bio-physical constraints and processes (Antles and Capalbo, 2001). In this study, the bio-economic simulation model is used to conduct a comparative analysis of the impacts of two alternative water pricing systems – (a) the current flat rate per hectare pricing, and (b) a volumetric pricing – in terms of economic efficiency of water allocation, environmental flow requirements and cost recovery.

AquaCrop, an agronomic model developed by FAO (Steduto, Hsiao, Raes, & Fereres, 2009), was used as the crop growth model. AquaCrop simulates crop growth from sowing to harvest on a daily time scale. It simulates the crop growth process as a function of the climate and the farmer’s technical decisions (irrigation, soil management practices, etc.). AquaCrop has been validated under various conditions in Sub-Saharan Africa (Khoshravesh, Mostafazadeh-Fard, Heidarpour, & Kiani, 2012). AquaCrop allows the building of a data-set specifying irrigation water quantities and the corresponding yield. The data-set can then be used to estimate production functions. Separate production functions were estimated for wet-season rice, dry-season rice and sugar cane (see Appendices 1 and 2). Also, in the baseline scenario, the model has been calibrated to reflect the yields obtained by different categories of farmers (small-scale and large-scale).

With respect to the economic model, the objective of the farmer is to maximize profit, while the objective of the manager, i.e. the ON, is to maximize agricultural production, taking into account water availability and budget constraints. The optimal volumetric price is determined in the model by respecting all the constraints and optimization conditions. The mathematical model was made operational using a solver-type algorithm. This formulation is perfectly in line with the objective



Source : d'après Office du Niger. Mars 2010. Ségou, Mali.

Figure 1. Map showing the location of three major schemes studied in the Office du Niger area.

of Malian agricultural policy (Loi d'Orientation Agricole, 2005). The profit of the farmer is defined as the value of agricultural production less variable costs, including the cost of water and other production costs (land preparation, weeding, harvesting, etc.). Each investor is assumed to grow only one of two crops, rice or sugar cane. Rice is grown twice per year, sugar cane only once. These assumptions are consistent with observations and agricultural production practices of large-scale investors in the ON (see Appendices 1 and 2).

The solution to this problem is characterized as follows. If a flat per area rate is applied, then the price is independent of the amount of water used. Theoretically, the farmer would tend to choose to use all the available water. But in practice, the farmer is limited by his/her water abstraction capacity. Under a uniform volumetric pricing system, the farmer will choose an amount of water that equates the marginal productivity of water to the relative price of water. This means that an increase in water price will lead the farmer to reduce water consumption. Also, because the water price is the same for both crops (rice and sugar cane), optimization involves that the marginal water productivity for both crops is equal. This is done by reallocating water from the less productive crop to the more productive one. The mathematical details are specified in Appendix 1.

Data sources

Agricultural and climatic data from various previous studies in the ON were used to estimate and calibrate the crop growth model (Kuper & Tonneau, 2002; Reseau riz, 2004; Tangara, 2011). Soil data from the Harmonized World Soil Database, combined with soil-type-specific default values of AquaCrop, were used (FAO/IIASA, 2012). Climatic data were extracted from the FAO ClimWat database (CLIMWAT, 2011). Economic information on prices and costs was obtained from AMASSA/Afrique Verte Mali (2014) and Mather and Kelly (2012), and completed and confirmed in recent interviews with top ON managers.

Three scenarios were tested. Scenario 1 mimics the baseline conditions in terms of area planted to different crops and yields. Scenario 2 assumes that existing land investors implement their production plans. Scenario 3 assumes that new additional land investments are implemented. These assumptions are based on the contractual agreements of current investors with ON and in-depth interviews with senior managers of ON. The assumptions are also consistent with the ON Development and Master Plan that was validated in 2008.

Figure 2 shows the production functions for wet-season rice, dry-season rice and sugar cane. All production functions are increasing and concave, which is consistent with micro-economic theory. Rice production in the wet season is higher than in the dry season, because agro-climatic conditions (temperature, humidity, etc.) in the wet season are more favourable to rice growth. Sugar cane production increases considerably with more water. But for water allocation purposes what matters is not the overall production per se but the marginal production, as will be shown below.

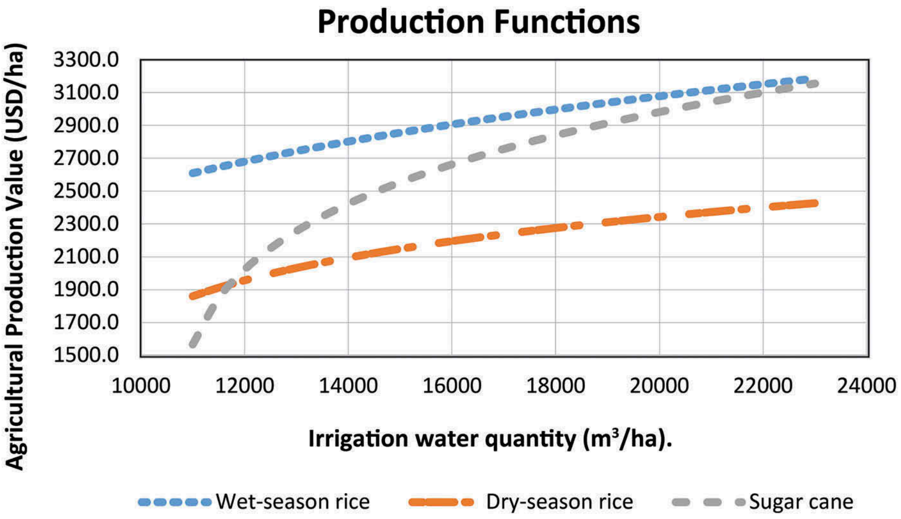


Figure 2. Estimated rice and sugar cane production functions.

Impacts of different pricing systems on water management

Scenario 1: baseline

The baseline scenario is constructed based on observed yields in the ON area for smallholder farmers. The average rice yield is about 6.2 T/ha, with 6.5 T/ha in the rainy season (on 96,000 ha) and 4.5 T/ha in the dry season (on approximately 22,000 ha); sugar cane yield is 74.5 T/ha on 9000 ha (FAOSTAT, 2010; Tangara, 2011). The associated water demands are 10,900 m^3/ha and 10,200 m^3/ha for rice and sugar cane, respectively. Water demand is higher in the rainy season than the dry season, probably because due to other climatic conditions (evapotranspiration, temperature, humidity), the marginal crop production per unit of water is higher in the rainy season than in the dry season. Therefore, farmers have more incentive to irrigate in the wet season. When aggregated at the ON level, and considering an irrigation efficiency of 0.4 in the ON area (Kuper, Tonneau & Bonneval, 2002), this represents an annual water demand of about 3.52 km^3 according to the model. This simulated result approximates with a high degree of accuracy (about 2% difference) the actual irrigation water withdrawal in the ON (based on official ON data), showing the validity of the model (Tables 1 and 2).[3]

The total amount of water fees that can be potentially collected by ON is USD 18.8 million per year. This amount is a third of the ON's annual budget (USD 54.7 million, according to Maliweb, 2014), without considering the fact that the fee recovery rate is only 90%. The budget gap is met by the state and other technical partners every year.

Scenario 2: implementation of the plans of LSIALs

In this scenario, we assume that large-scale investments like Malibya (100,000 ha) for rice and N-Sukala (15,000 ha) and Sosumar (20,000 ha) for sugar cane are

Table 1. Baseline scenario: economic output per ha without large-scale investments in agricultural land.

	Yield (T/ha)	Production (USD/ha)	Water demand (m^3/ha)	Farmer net profit (USD/ha)	Office du Niger revenue (USD/ha)
Wet-season rice	6.5	2,601.07	10,900	1,756.58	138
Dry-season rice	4.5	1,798.40	10,200	1,156.58	138
Sugar cane	74.5	2,980.01	15,060	2,104.01	276

Note. The current water price is USD 138/ha for rice and USD 276/ha for sugar cane. The water price of sugar cane is twice that of rice because sugar cane takes two seasons to mature while rice needs only one. Conversion from XOF to USD was made on the basis of 500 XOF = USD 1, according to BCEAO, 9 March 2014. Market price for rice and sugar cane are USD 400/t and USD 40/t, respectively. The other production costs (apart from water) are USD 568.5/ha for rice and USD 600/ha for sugar cane, respectively.

Table 2. Aggregate economic output for the Office du Niger without large-scale investments in agricultural land.

	Area ('000 ha)	Production (USD millions)	Water demand (million m^3)	Office du Niger revenue (USD millions)
Wet-season rice	96	250	2,616	13
Dry-season rice	22	40	563	3
Sugar cane	9	27	339	2
Total	127	316	3,518	18

implemented. This will bring the area under rice cultivation to 196,000 ha, and the area for sugar cane to 44,000 ha.

With increased irrigated area, it is likely that the budget requirement of ON will also increase, as there will be a need to construct more infrastructure (roads, canals, etc.) and maintain it. Assuming that the increase in budget is roughly proportional to the developed irrigated area (Perry, 2001; Venot, Andreini, & Pinkstaff, 2011), the ON budget requirement will be about USD 154 million per year. Tables 3 and 4 show two different options with the assumption of a flat rate per hectare water pricing and a volumetric linear pricing system. Rice yields in the area can reach up to 7.5 T/ha in the wet season and 5.5 T/ha in the dry season (Brondeau, 2011; Tangara, 2011).[4]

With the amount of water abstracted from the river, the volumetric water pricing (USD 0.045154/m^3) allows an increase in agricultural production value of about USD 2 million per year. This is because volumetric pricing allows an efficient reallocation of water between rice and sugar cane. In fact, while the rice yield in the dry season virtually did not change and there is only a slight decrease in wet-season rice yield (about 0.1 T/ha), sugar cane yield increases from 75 T/ha to 81.8 T/ha (an augmentation of 6.8 T/ha). This indicates that the marginal value of water is higher in sugar cane compared to rice production.

Considering the ON revenue, the flat rate per area water pricing does not allow the recovery of the budget (only a third is collected), while with volumetric water pricing, fees collected exceed the budget requirement by a wide margin due to the tremendous increase in water demand (approximately 15.38 km^3). However, the ON could still use a flat rate to cover this budget gap by increasing its level, provided

Table 3. Scenario 2: economic output per ha under current large-scale investments in agricultural land.

Flat per ha water pricing (USD 138/ha for rice, USD 276/ha for sugar cane)

	Yield (T/ha)	Production (USD/ha)	Water demand (m^3/ha)	Farmer net profit (USD/ha)	Office du Niger revenue (USD/ha)
Wet-season rice	7.5	3,000.73	18,100	2,156.24	138
Dry-season rice	5.5	2,199.83	15,800	1,355.34	138
Sugar cane	75	2,999.57	15,365	2,017.08	276

Volumetric water pricing (USD 0.045154/m^3)

	Yield (T/ha)	Production (USD/ha)	Water demand (m^3/ha)	Farmer Net Profit (USD/ha)	Office du Niger revenue (USD/ha)
Wet-season rice	7.4	2,956.73	17,096	1,616.28	771.96
Dry-season rice	5.5	2,189.53	15,569	918.03	703.01
Sugar cane	81.8	3,270.98	20,478	1,639.83	924.66

Table 4. Scenario 2: Aggregate economic output for the Office du Niger under current large-scale investments in agricultural land.

Flat per ha water pricing (USD 138/ha for rice, USD 276/ha for sugar cane)

	Area (1000 ha)	Production (USD millions)	Water demand (million m^3)	Office du Niger revenue (USD millions)
Wet-season rice	196	588	8,869	27
Dry-season rice	122	269	4,822	17
Sugar cane	44	132	1,690	12
Total	362	989	15,381	56

Volumetric water pricing (USD 0.045154/m^3)

	Area (1000 ha)	Production (USD millions)	Water demand (million m^3)	Office du Niger revenue (USD millions)
Wet-season rice	196	580	8,377	151
Dry-season rice	122	267	4,752	86
Sugar cane	44	144	2,253	41
Total	362	991	15,381	278

ON is willing to raise water fees considerably, to around USD 425/ha for all water users. Taking into account the evaporation of water from the river (0.57 km^3), the minimum environmental flow requirement (estimated at 1.5 km^3 – MCA, 2008; Zwarts, Van Beukering, Kone, & Wymenga, 2005) will not be met once every 10 years. But the next scenario is even more alarming.

Scenario 3: more investments

Considering the strong interest of investors in the area and expansion activities planned by the ON, more investments in the ON area can be expected. These investments will translate into more land being developed and inefficient increased water use, if proper water management systems are not put in place. This scenario assumes that 100,000 ha more land than in Scenario 2 is put to rice production through various future projects (for example the Millennium Challenge Account project and ON's own investment). As with Scenario 2, the effect of the business-asusual water valuation system (flat rate per ha) is compared to that of a volumetric water pricing (Tables 5 and 6).

This scenario clearly shows the limitations of the current water management and valuation system. Water demand explodes (to about 24 km^3) and nearly equals the average annual available water at the Markala Dam (about 25 km^3).[5] This scenario will not meet the environmental requirement and is likely to result in conflicts among different categories of users. Large-scale farmers with considerable water abstraction capabilities are likely to appropriate the major share of the resource, to the detriment of smallholders (Coulibaly, Bélières, & Koné, 2006). At a volumetric price of USD 0.055815/m^3, water use will come down to about 20 km^3. This will have limited effect on agricultural production, but will help reduce conflicts among water users, and environmental needs will be covered (at least on average). The volumetric water pricing can be designed to conserve more water and even better cover the environmental needs.

Discussion and conclusions

There are two important limitations to the approach used in this article. First, the bio-economic model used assumes that water pricing has effects only on water use and influences yield mainly through changes in irrigation level. This is a simplification, as water pricing may also affect the use of other inputs (Frija, Wossink, Buysse, Speelman, & Van Huylenbroeck, 2011; Speelman et al., 2009). The AquaCrop model represents a trade-off between specifying a complex detailed model and the substantial data requirements for running such a model. Besides, other studies suggest that substitutions between water and other inputs tend to be limited (Lehmanna & Finger, 2014; Schoengold, Sunding, & Moreno, 2006). Second, although a dynamic and adaptive pricing system could have been used to address the environmental flow requirements much more deeply, the use of such a sophisticated model would require information and data on the hydrology of the whole basin and operational rules for water release from the planned Fomi Dam upstream of the ON area, which were unavailable to the authors.

Table 5. Scenario 3: economic output per ha with additional large-scale investments in agricultural land.

Flat per ha water pricing (USD 138/ha for rice, USD 276/ha for sugar cane)					
	Yield (T/ha)	Production (USD/ha)	Water demand (m^3/ha)	Farmer net profit (USD/ha)	Office du Niger revenue (USD/ha)
Wet-season rice	7.5	3,000.73	18,100	2,156.24	138
Dry-season rice	5.5	2,199.83	15,800	1,355.34	138
Sugar cane	75	2,999.57	15,365	2,017.08	276
Volumetric water pricing (USD 0.055815/m^3)					
	Yield (T/ha)	Production (USD/ha)	Water demand (m^3/ha)	Farmer Net Profit (USD/ha)	Office du Niger revenue (USD/ha)
Wet-season rice	7.0	2,804.13	14,048	1,451.56	784.09
Dry-season rice	5.3	2,107.28	13,926	761.49	777.31
Sugar cane	77.5	3,098.04	17,023	1,441.40	950.15

Table 6. Scenario 3: Aggregate economic output for the Office du Niger with additional large-scale investments in agricultural land.

Flat rate per ha water pricing (USD 138/ha for rice, USD 276/ha for sugar cane)

	Area (1000 ha)	Production (USD millions)	Water demand (million m^3)	Office du Niger revenue (USD millions)
Wet-season rice	296	888	13,394	41
Dry-season rice	222	489	8,772	31
Sugar cane	44	132	1,690	12
Total	562	1,509	23,856	84

Volumetric water pricing (USD 0.055815/m^3)

	Area (1000 ha)	Production (USD millions)	Water demand (million m^3)	Office du Niger revenue (USD millions)
Wet-season rice	296	830	10,395	232
Dry-season rice	222	468	7,732	173
Sugar cane	44	136	1,873	42
Total	562	1,434	20,000	447

Despite these caveats, the analysis presented exposes the economic, social and environmental problems that are unintentionally ignored but are likely to arise when water availability and utilization by various users, especially rich investors, are not taken into consideration in the approval and/or planning of LSIALs. Water resources appear to be one of the main drivers of land acquisition in the ON area. As more water-demanding crops (e.g. rice and sugar cane) are cultivated on large tracts of land, there will be a pressing need to improve the water management system. Although there is an implicit recognition by the managers of ON of the need to efficiently allocate water, cover the cost of water supply and ensure environmental flows to guarantee the long-term sustainability of the irrigation and farming systems, an efficient water valuation and management system that will allow these objectives to be achieved has not been considered or implemented. The analysis indicates that the flat rate per hectare pricing system as currently implemented by ON will not allow the managers to achieve efficient water allocation. With the current pricing system, under the second and third scenarios considered, the Markala dam will not even come close to irrigating the million-hectare area that is generally claimed to be irrigable.

As demonstrated, volumetric water pricing that allows the marginal value of water to be reflected in water allocation decisions is an option to address the inadequacy of the current pricing system. In this article, a linear volumetric pricing model was used as a first alternative to a flat rate per area pricing system. But volumetric pricing can take many innovative forms to suit the objectives of policy makers, including assessment of trade-offs between efficiency and equity. It can also allow environmental flows to be directly taken into consideration. While environmental management is not in the mandate of the ON, the inner delta of the Niger River has sensitive ecosystems and a unique biodiversity providing several services. Including environmental preservation and management in the mandate of the ON will allow these ecological systems to be taken into consideration and managed in a more integrated way, partly through the pricing system used by the agency.

However, problems associated with the practical implementation of volumetric pricing should not be ignored (Cornish, Bosworth, Perry, & Burke, 2004; Easter & Liu, 2005). Meters will have to be installed to measure the volume of water delivered, and they will have to be transparently and honestly read and reported. As long as the cost of installing measuring devices, monitoring water use and managing a billing system is not a high percentage of the revenue collected or of the value of production, volumetric water pricing can be justified. In the context of the large-scale investments considered, the installation and monitoring of volumetric systems would be easier and less costly, because there will be room for economies of scale in metering water use and in collecting water fees. The ON is already planning to install water metering systems, at least for some schemes (PIA, 2011). More generally, water pricing is a controversial and politically sensitive subject in many developing countries. Thus, the inclusion of political considerations in economic approaches to water pricing reform is highly desirable, as suggested by Dinar (2000). Indeed, ignoring political considerations can hinder the implementation of pricing systems designed only on efficiency basis (Molle, Venot, & Hassan, 2008; Dinar & Wolf, 1997), because water pricing reforms necessarily involve changes in institutional arrangements, since they are not just about changes in price levels but imply a change of the pricing rules. Moving from flat-rate area-based pricing to volumetric water pricing requires institutional reforms to make the change socially and politically acceptable. Approaches that involve farmers, through water user associations, in volumetric pricing are necessary and could prove useful.

Notes

1. Out of 177 documented land deals reviewed by the authors in Africa, only 8 explicitly mentioned water management.
2. This figure varies according to the source considered.
3. Assuming that water use is proportional to area cultivated, water withdrawal is projected for the presently developed area based on data from Traore (2008).
4. It is assumed that with the continuous improvement in rice yields, these values will be reached under the present pricing system.
5. Based on data from Traore (2008).

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Appendix 1. Economic model and estimation of climate-dependent rice and sugar cane production functions

Economic model

A traditional micro-economic model is used. The objective of the farmer is to maximize profit, while the objective of the manager is to maximize agricultural production, taking into account water availability and budget constraints. The problem can be viewed as a Stakelberg competition, where the manager is the leader and the farmer the follower. Crops (rice and sugar cane) are sold at their respective market prices. Crop growing requires water and other inputs that have costs (land preparation, harvesting, etc.). A production function 'tells' how much yield is obtained for how much water (Steduto et al., 2009). The farmer's problem and the manager's problem are formalized as shown below.

Farmer's problem

The objective of the rational farmer is to choose the irrigation water quantity he/she uses so as to maximize his/her profit. The profit is defined here as the value of agricultural production minus water cost and other farm costs. The rational farmer's problem can be written as:

$$\max_{w_i}\left(p_{y_i}Y_i(\pi+w_i)-p_w w_i-c\right)A_i \tag{1}$$

where $Y_i()$ represents the production function for crop i. It is assumed to be increasing and concave ($Y_i' > 0$, $Y_i'' < 0$), which is a common assumption in agricultural economics. Further, this functional form is confirmed when Y_i was estimated. The estimation procedure is explained in a subsequent section.

Description of variables

A_i is the area under crop i
w_i is the irrigation intensity of crop i (i = 1 for rice, 2 for sugar cane)
c represents other farm costs (land preparation, harvesting, etc.)
π is the average rainfall level.
p_{y_i} is the market price of crop i
p_w is the unit water price.

The solution to this problem is given by the first-order condition:

$$w_i = Y_i'^{-1}\left(\frac{p_w}{p_{y_i}}\right)-\pi \tag{2}$$

This represents water demand. It increases with the crop market price (rice or sugar cane) and decreases with water price. Therefore, an increase in water price will lead to water saving, which can be quantified for the individual farmer using Equation (2). Summing over all farmers, *unwantedcommandusedinTEX..Pleaseremove* $\sum^{w_i}$, gives the total water use.

Water manager's problem

The water manager's problem is to choose the water price p_w so as to maximize a social welfare function that takes into account the objectives of all user groups. The social welfare function here is the value of total agricultural production of rice and sugar cane (for all farmers):

$$\max_{p_w}\sum_{i}^{n}A_i p_{y_i}Y_i(\pi+w_i)$$

under the following constraints:

Water availability constraint

$$\sum_{i}^{n}A_i w_i \le W - W_E$$

Budget constraint

$$\sum_{i}^{n} A_i p_w w_i \geq B$$

where

n is the number of farms

W is the total water availability (W_{E} represents the environmental water requirement)

B represents the part of costs or budget that the manager wants to recover.

This problem is mathematically solved using the Lagrangian. The Lagrangian of this equation can be written as:

$$\max_{p_w} L(p_w, \lambda_w, \lambda_B) = \max_{p_w} \sum_{i}^{n} A_i p_{y_i} Y_i(\pi + w_i) - \lambda_w \left(\sum_{i}^{n} A_i w_i - (W - W_E) \right) + \left(\sum_{i}^{n} A_i p_w w_i - B \right)$$

The first-order conditions give:

$$\sum_{i}^{n} A_i \left(\tfrac{p_w}{p_{y_i}} Y_i^{\prime -1^\prime} \left(\tfrac{p_w}{p_{y_i}} \right) - \lambda_w \left(\tfrac{1}{p_{y_i}} Y_i^{\prime -1^\prime} \left(\tfrac{p_w}{p_{y_i}} \right) \right) + \lambda_B \left(Y_i^{\prime -1} \left(\tfrac{p_w}{p_{y_i}} \right) + \tfrac{p_w}{p_{y_i}} Y_i^{\prime -1^\prime} \left(\tfrac{p_w}{p_{y_i}} \right) \right) \right)$$

The water constraint is binding when $\lambda_w > 0$ and $\lambda_B = 0$. In that situation, we have $\lambda_w = p_w$, implying that the water price perfectly reflects water scarcity across all crops. The budget constraint is binding when $\lambda_w = 0$ and $\lambda_B > 0$. We then have:

$$\lambda_B = - \frac{\sum_{i}^{n} A_i Y_i^{\prime -1} \left(\frac{p_w}{p_{y_i}} \right)}{\sum_{i}^{n} A_i \frac{p_w}{p_{y_i}} Y_i^{\prime -1^\prime} \left(\frac{p_w}{p_{y_i}} \right)} - 1$$

The next step is to estimate $Y(w)$, which will feed into the economic model.

Estimation of crop production functions

As previously explained, the AquaCrop crop growth model (Steduto et al., 2009) is used to estimate the crop production functions. Based on insights from previous works, a flexible functional form that is suitable for most crops and climatic conditions is used to estimate crop yield functions for given levels of irrigation. The functional form is specified as:

$$Y(w) = \alpha_1 (w + \alpha_2)^{\alpha_3}$$

where α_1,α_2 and α_3 are regression coefficients to estimate.

Table A1 reports the estimated values of the regression coefficients for wet-season rice, dry-season rice and sugar cane. The model passed the χ^2 and Fischer test at 95% (χ^2 tests the

Table A1. Production function coefficients.

	Wet-season rice	Dry-season rice	Sugar cane
α_1	1.11	1.40	11.53
α_2	−4,000.00	−8,450.29	−10,599.48
α_3	0.200	0.153	0.204
Emp *F*	11.11	251.72	591.33
Emp χ^2	0.01892394	0.00202189	0.04891976

Table A2. Prices and costs.

	Rice	Sugar cane
Market Price (USD/T)	400.00	40.00
Other production costs (USD/ha)	568.50	600.00

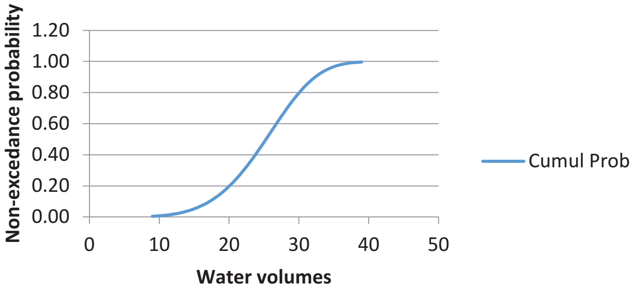

Figure A1. Cumulative probability of obtaining given water volumes.

hypothesis that the observed distribution is consistent with the assumed functional form, while the Fischer value tests the significance of the coefficients).

These functions are then used as inputs in the economic model presented in the previous section. An optimization module is then used to simulate the different output variables. Table A2 summarizes the main economic assumptions used. The assumptions are based mainly on AMASSA (2014) and Mather and Kelly (2012).

Based on flow records from 1982 to 2007, the cumulative probability distribution of available water volumes is esimated. This allows knowing the probability that a given volume of water will not be obtained. It is assumed that the data follow a Weibull distribution (as is often the case for flow data) and validate the assumption with Student and Fischer tests. This analysis suggests that the flow follows a Weibull distribution, with $\alpha = 4.893$ and $\beta = 10{,}559{,}747.318$. The distribution function is represented in Figure A1.

Appendix 2. Parameterization of the AquaCrop crop growth model

Tables B1 and B2 show the soil and crop parameters used.

Table B1. Soil parameters.

Soil	
Description	Sandy loam
Thickness (m)	4
PWP (%)	10
FC (%)	22
SAT (%)	41
TAW (mm/m)	120
KSAT (mm/day)	500

Sources: Harmonized World Soil Database and AquaCrop.

Table B2. Crop parameters.

Region	Crop	Planting date	Harvest index (%)	Sowing density (plants/m^2)
Segou	Wet-season rice[1]	19/06	43	100
Segou	Dry-season rice	19/10	43	100
Segou	Sugar cane	19/06	82	14

Sources: Kuper and Tonneau (2002) used for calibration.
Note. Additional parameterization files are available upon request.
[1] Rice variety considered is ITA 304 (Reseau riz, 2004).