



(RESEARCH ARTICLE)



IDENTIFICATION AND ESTIMATION OF WATER LOSSES ALONG THE HEAD REACH OF THE MAIN CANAL OF THE BAGUINÉDA IRRIGATION SCHEME (OPIB, MALI): THE CASE OF UNAUTHORIZED OFFTAKES

Mamadou GUINDO ^{1, 2, 3, *}, Sory DIALLO ¹, Moussa THIAM ¹ and Lassine SOUMANO ⁴

¹ Teacher Training School for Technical and Vocational Education (ENETP), Department of Civil Engineering, Hydraulics Laboratory, Bamako, Mali.

² University of Sciences, Techniques and Technologies of Bamako (USTTB), Bamako, Mali.

³ Doctoral School of Sciences and Technologies of Mali (EDSTM), Mali.

⁴ Rural Polytechnic Institute for Training and Applied Research (IPR/IFRA), Mali.

* Corresponding Author

ORCID Details

Mamadou GUINDO: <https://orcid.org/0009-0003-5869-5335>

Moussa THIAM: <https://orcid.org/0009-0009-8880-0136>

World Journal of Advanced Research and Reviews, 2026, 32(01), 040–052

Publication history: Received on 22 August 2026; revised on 28 September 2026; accepted on 30 September 2026

Article DOI: <https://doi.org/10.30574/wjarr.2026.32.1.2520>

Copyright © 2026 Author(s) retain the copyright of this article. This article is published under the terms of the Creative Commons Attribution License 4.0

ABSTRACT

The Baguinéda Irrigated Perimeter Office (OPIB), located 35 km east of Bamako on the right bank of the Niger River, operates a 3,000-ha gravity irrigation scheme. In a context of climate change and low river floods, this peri-urban scheme suffers from numerous unauthorized connections (pipes and motor pumps) along the head reach of its main canal, a 10-km section with no official offtake. These withdrawals reduce network efficiency and aggravate the water deficit during the dry season.

This study aims to identify these offtakes, estimate their discharges, and assess their impact on water delivery to the scheme.

The installations were inventoried in the field using a Garmin GPS receiver and a survey form, and then mapped in QGIS. Discharges were estimated from manufacturer data for the motor pumps and from the pipe (submerged-orifice) equation for the direct connections.

Eighty-nine (89) unauthorized offtakes were identified (62 pipes and 27 motor pumps), with diameters ranging from 63 to 300 mm, for an estimated total withdrawal of 1.783 m³/s. Relative to the main canal discharge (10.878 m³/s), this withdrawal represents a loss of 16.4%, with a severe impact on the dry season.

Measures are proposed to reduce these losses, improve network efficiency, and strengthen OPIB's own revenue by formalizing these offtakes through a water fee.

Keywords: Irrigation, Baguinéda, Water Losses, Illegal Withdrawals, Efficiency

1 INTRODUCTION

Mali is a landlocked country in West Africa covering an area of about 1.24 million km², 51% of which is desert. Cultivated land (arable land and land under permanent crops) covers 4.7 million ha, i.e., 4% of the territory. The country shares its borders with seven countries: Algeria to the north, Niger to the east, Burkina Faso and Côte d'Ivoire to the south, Guinea to the southwest, Senegal to the west, and Mauritania to the west and northwest (1).

The Malian economy depends heavily on the rural sector, in which agriculture holds a major strategic position owing to its share of the labor force (79%) and its contribution to gross domestic product (37% of GDP). Agricultural production suffers from low and erratic rainfall. Over the past thirty years, beyond the irregularity of rainfall, the country has experienced a decline in precipitation and a southward advance of desertification, which have made rural populations highly vulnerable to food shortages and have thus increased poverty (2).

In Mali, current water use by the irrigation sector amounts to about 5.9 km³/year,

i.e., 90 percent of total withdrawals; it is drawn almost entirely from surface water resources and occurs almost entirely within a six-month period. Irrigation of wet-season crops generally poses no problem, given the relatively high river flows during this period. By contrast, dry-season water use, although small, occurs at a time when river flows and reservoir levels are low.

Given the scale of agricultural withdrawals from the Niger River, the Baguinéda scheme ranks among the large irrigation schemes that abstract water from the river.

The Baguinéda hydro-agricultural scheme is a very old development dating back to the 1920s. It is located 30 km northeast of Bamako on the right bank of the Niger River and currently covers about 3,000 ha of alluvial terraces out of the 4,500 ha of the valley in this area. It is gravity-fed from an intake on the Niger River, the "Aigrettes dam". This intake also supplies the Sotuba hydroelectric power plant, 2,800 m downstream (3).

However, although most of the main canal is lined (about 85%), unauthorized connections are still found along its head reach. These connections considerably reduce network efficiency and cause excess water consumption at the intake.

In addition to motor pumps, unauthorized offtakes generally consist of PVC or metal pipes of various diameters buried in the canal embankment, without any upstream control device. Their discharge depends on the water head in the canal (4).

According to an inventory carried out in March 2014 by a local consulting firm, at least ten offtakes were visible; based on the number of pumps and illegal offtakes observed, the maximum instantaneous withdrawal was estimated to potentially reach 1 m³/s (5).

Water losses in an irrigation network cause water shortages, which are one of the direct causes of reduced performance in an irrigation system. These losses lead to reduced water pressure, poor water distribution, higher operating costs, and lower network efficiency (6).

The objective of this work is to identify and estimate the water losses caused by unauthorized offtakes along the head reach of the OPIB main canal.

The specific objectives are to: (i) identify the unauthorized offtakes along the head reach; (ii) estimate the discharges withdrawn by these offtakes; and (iii) propose corrective measures for these withdrawals.

2 MATERIAL

2.1 Study area

The Baguinéda irrigation scheme, which constitutes our study site, is a hydro-agricultural development managed by the Baguinéda Irrigated Perimeter Office (OPIB). The GPS coordinates of the site are 7°46'30" W and 12°37'45" N. It is located in the rural commune of Baguinéda-Camp, 30 km southeast of Bamako, the capital of Mali, on the right bank of the Niger River, and covers 22 villages. The commune of Baguinéda-Camp, with an area of about 990 km², is bounded to the north by the communes of Tienfala and Koulikoro, to the south by the communes of Mountougoula and N'Goubara,

to the east by the rural commune of Binko, and to the west by the commune of Kalaban-Coro and Commune VI of the District of Bamako (7).

The Baguinéda irrigation scheme is an old development created in 1926 and currently covers about 3,000 ha of alluvial terraces out of the 4,500 ha of the valley in this area. It is gravity-fed from an intake on the Niger River (the Aigrettes diversion weir). This intake also supplies, 2,800 m downstream, the Sotuba hydroelectric power plant, built in 1966. After several decades, the level of operation of the scheme had declined sharply, and some parts had even been abandoned by the early 1980s. This difficult situation led the Government of Mali, from 1987 onwards, to seek the support of Japanese cooperation (JICA) and of the Bank for the rehabilitation of the main infrastructure and the resumption of development works (3).

The scheme is accessible via the paved national road RN6 (Bamako–Ségou) and via a branch road, known as the farm road, which lies within the OPIB domain and is also paved from Tabacoro (locally called “Pied”) to Baguinéda-Camp. From there, the scheme is accessed by a laterite track running along the main canal, which can only bear limited wheel loads because of the nature of its structures (8).

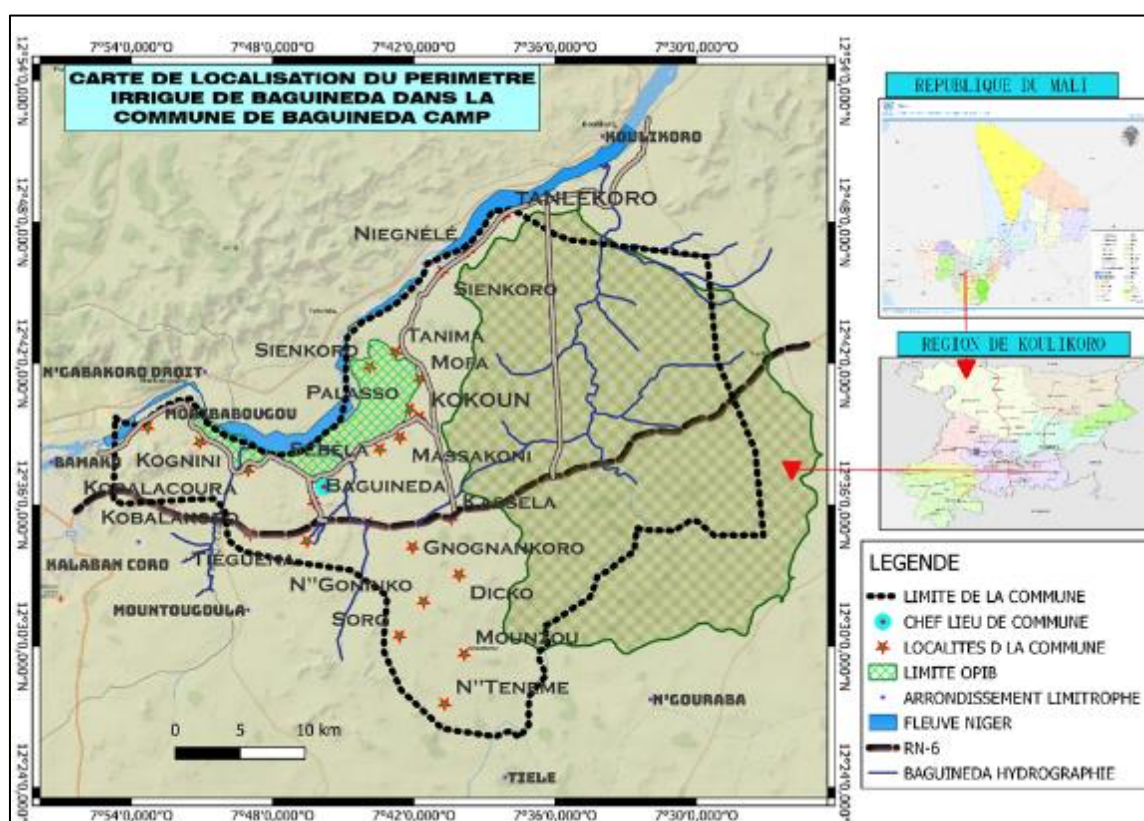


Figure 1: Location map of the Baguinéda irrigation scheme in the commune of Baguinéda-Camp

2.2 Physical setting

- **Climate:** The climate of the area is Sudanian, with three seasons: a cool dry season (November to February), a hot dry season (March to May), and a rainy season (June to October), August and September being the wettest months. Annual rainfall ranges from 900 to 1,200 mm (mean of about 1,000 mm), nearly 80% of which falls from July to September. Two winds prevail: the Harmattan, a hot, dry wind originating from the Saharan anticyclone, which blows during the dry season (November to April–May), and the monsoon, a warm, humid wind of maritime origin, which brings the rains. The mean annual temperature is 27.9 °C, with minima in December–January (16.4 °C) and maxima in April–May (38 °C) (8).
- **Relief and vegetation:** The relief is dominated by a sandstone escarpment capped by a lateritic duricrust and bordered on the river side by colluvium; toward the east of the scheme (Sébéla–Tanima), it gives way to a flat alluvial fringe. The vegetation is of the Sudanian type (savanna associated with a more or less dense shrub layer), except for a few gallery forests along the thalwegs periodically flooded by the Niger River.
- **Water resources:** The Niger River, the scheme's source of water, has a flood period from June to September (peaking in September) and a recession period from October to May (minimum in May). Its mean flood

discharge is estimated at $1,512 \text{ m}^3/\text{s}$ and its low-flow discharge, regulated by the Sélingué dam, at $100 \text{ m}^3/\text{s}$. Since the turbines of the Sotuba hydroelectric power plant were shut down, the scheme has withdrawn $10 \text{ m}^3/\text{s}$ in the wet season (rice only) and in the dry season (mainly vegetables and rice), i.e., 0.66% and 10% of the river discharge, respectively (5).

2.3 Hydraulic infrastructure of the study area

2.3.1 Irrigation network

The Baguinéda scheme is irrigated from the Niger River through a hierarchical network (primary canal and secondary, tertiary, and quaternary canals). The present study focuses on the upstream head reach of the main canal.

In this work, the head reach (*tête morte*) of the main canal is defined as the section of the conveyance canal located upstream of the first offtake and having no distribution structure. Unlike the active sections of the network, this reach does not directly contribute to plot irrigation and is particularly vulnerable to water losses, notably in the presence of unauthorized offtakes or leakage (9–11).

The primary network comprises: (i) the Aigrettes dam, a run-of-river structure consisting of an 800-m fixed masonry weir and a movable section of 4 bays with manually operated gates; (ii) the feeder canal intakes, 16 bays built under the Sotuba 2 project of Énergie du Mali (EDM) and combined with a crossing structure; (iii) the feeder canal, 3 km long, which conveys $138 \text{ m}^3/\text{s}$, of which $10 \text{ m}^3/\text{s}$ is for the scheme and $128 \text{ m}^3/\text{s}$ for the hydroelectric power plant; and (iv) the Sotuba main canal intake, equipped with two $2.5 \text{ m} \times 2 \text{ m}$ flat gates (maximum opening of 10 m^2) with hydraulic control operated by EDM, and with upstream and downstream staff gauges for measuring the head loss (3,5,8).

The main canal, 35.7 km long, extends from the Sotuba intake to regulator No. 7. It is divided into seven reaches separated by fixed-crest semicircular regulators that maintain the water levels required to supply the secondary canals. It serves 52 secondary offtakes and includes numerous ancillary structures: 7 regulators, 24 siphons (including the inverted siphon of Kobaj), 7 flood spillways, 15 bridges, 13 washing places, 7 livestock watering points, 6 safety overflow weirs, and 2 water hyacinth traps. Two irrigation blocks are also connected to it: Sienkoro (345 ha) and Tanima (345 ha) (3,5,8).

2.3.2 Drainage network

The OPIB drainage network conveys surplus irrigation water and runoff to the Niger River to protect the soils from waterlogging.

It is organized into four hierarchical levels:

- Primary drain: formed by the Fara River (reshaped and realigned) and the main drain.
- Secondary drains: collect water from the tertiary drains and runoff; they are lined by a track with a usable width of 4.00 m.
- Tertiary drains: run along the irrigation units and include 0.5-m vertical drops to prevent erosion where the flow velocity exceeds 1 m/s ; they are lined by a 3.00-m track.
- Quaternary drains (field ditches): provide both water distribution and drainage at plot level, discharging through a 200-mm-diameter PVC pipe (6 m long) under the bund.

The network is designed for an internal drainage modulus of 5 L/s/ha and external inflows of $0.49 \text{ m}^3/\text{s/km}^2$ (for a 10-year return-period rainfall of 102 mm in 24 h). Keeping it in good condition requires regular weed cutting (notably between 15 August and 15 October) to control the proliferation of aquatic vegetation and erosion (3).

2.4 Materials

Data collection and processing relied on the following equipment and software:

- **Field equipment:** A Garmin handheld GPS receiver with an accuracy of 1 m was used to georeference the unauthorized offtakes. A measuring tape and a millimeter-graduated rule were used to measure pipe diameters and lengths. A camera was used to photograph the installations. Travel along the head reach was carried out by off-road motorcycle.
- **Software:** GPS coordinates were transferred and processed in AutoCAD 2020 and Covadis 17. Global Mapper and Google Earth were used to visually check positions on satellite imagery. The location map was produced in QGIS 3.44.12. Discharge calculations and graphs were produced in Microsoft Excel.
- **Secondary data:** OPIB technical archives were consulted, including irrigation network design studies, as-built drawings of the head-reach structures, and operating records. They provided the nominal characteristics of the main canal, the average modulated discharge of the secondary canals, and the areas allocated per season.

2.5 Field data collection

The field campaign lasted eight (8) survey days and covered the entire head reach, from the Sotuba intake (PK 0) to PK 8+514 m.

- **Inventory and georeferencing:** The entire head reach was surveyed on foot and by motorcycle along both banks. Each unauthorized withdrawal installation, whether a pipe crossing the embankment or a motor pump placed on the bank, was located by direct visual observation and then georeferenced by GPS. The chainage of each offtake was calculated in Covadis from the digitized canal centerline, and the positions were checked on satellite imagery.
- **Hydraulic characterization of the installations:** Two types of installations were distinguished.

For direct pipe connections, the inner diameter was measured with the graduated rule at the pipe inlet, and the length of the section crossing the embankment was measured with the tape; it does not exceed 20 m.

For motor pumps, the manufacturer's specifications (make, model, power, and suction and delivery diameters) were read from the nameplates and then cross-checked with suppliers on the local market. Semi-structured interviews were conducted with twenty (20) farmers available during the campaign, covering the type of motor pump, pipe diameter, delivery head, and daily operating time.

2.6 Estimation of withdrawn discharges

Pipe connections: The pipes crossing the embankment flow full (under pressure) under the water head of the canal. The withdrawn discharge was estimated using the submerged-orifice equation (12,13), applied to intake pipes according to the formulation adopted by (14):

$$Q = \alpha \cdot \frac{\pi d^2}{4} \cdot \sqrt{2gH} \quad (1)$$

where Q is the withdrawn discharge (m^3/s), α the discharge coefficient (dimensionless), d the inner diameter of the pipe (m), g the acceleration due to gravity (9.81 m/s^2), and H the available head (m), i.e., the difference between the canal water level and the pipe outlet level.

The coefficient α lumps together the contraction of the jet at the inlet and the friction losses along the pipe, according to $\alpha = \left(1 + K_e + f \cdot \frac{L}{D}\right)^{-\frac{1}{2}}$, where K_e is the entrance loss coefficient, f the friction factor, and L/D the pipe slenderness ratio. For a sharp-edged inlet ($K_e = 0.5$), a friction factor $f = 0.02$ representative of PVC, and a pipe length of about 6 m, this relationship yields $\alpha \approx 0.62$. The value $\alpha = 0.6$ was adopted, within the range of 0.6 to 0.8 commonly accepted for this type of structure. Pipe length is therefore not neglected: it is accounted for indirectly through the friction term $f \cdot L/D$ included in the coefficient α .

In the absence of a level survey of the offtakes, the head H could not be determined from the water surface and pipe elevations. It was estimated at 0.46 m and assumed to be uniform along the entire reach. The corresponding mean flow velocity, $V = \alpha \sqrt{2gH}$, is 1.8 m/s.

Motor pumps. Motor pump discharges were estimated from the manufacturers' nominal discharges, corrected for the total dynamic head measured on site. When the operator was absent, the characteristics were inferred from the model identified on the nameplate and from the measured pipe diameters.

Total withdrawn discharge. The total discharge was obtained by summing the individual discharges of the 89 installations inventoried. This summation assumes that all withdrawals operate simultaneously, a situation commonly observed in the dry season when water demand peaks. It therefore constitutes an estimate of the **installed withdrawal capacity**. In the wet season, when withdrawals are intermittent, the daily volume actually withdrawn by the motor pumps was estimated using an average operating time of 5 hours per day, derived from the interviews with farmers.

2.7 Data processing and analysis

Individual discharges were aggregated by installation type and diameter class. The longitudinal distribution of withdrawals was established as a function of chainage, and the cumulative withdrawal was expressed relative to the nominal discharge of the main canal. The total withdrawn discharge was then related to the average modulated discharge of an OPIB secondary canal, i.e., 171.5 L/s, which made it possible to estimate the average area irrigated by the unauthorized connections. The corresponding financial loss was assessed on the basis of the current water fees, i.e., 42,000 FCFA/ha in the wet season and 14,000 FCFA/ha in the dry season.

3 RESULTS AND DISCUSSION

3.1 Survey of the unauthorized offtake coordinates

Since the head reach of the main canal is lined, seepage and evaporation losses are minimal. The efficiency of the head reach is 0.85 (5). This efficiency does not account for withdrawals by unauthorized offtakes, which are the sole subject of this article.

In total, 89 unauthorized water offtake installations were identified along this section of the canal. The offtakes and their coordinates are listed in Table 1.

3.2 Pipe discharges

Pipe discharges were calculated using the equation given above in the Methods section. They are reported in the following table:

Table 1: Points equipped with pipes — chainage (PK), diameter, and withdrawn discharge

No.	PK	Ø (mm)	Q (m ³ /s)	No.	PK	Ø (mm)	Q (m ³ /s)
P04	0+188.372	110	0.017	P56	5+125.718	110	0.017
P05	0+245.258	63	0.006	P57	5+305.812	110	0.017
P11	0+480.081	85	0.010	P58	5+370.712	120	0.020
P13	0+573.205	105	0.016	P59	5+389.070	200	0.057
P28	2+127.236	105	0.016	P60	5+496.257	110	0.017
P29	2+146.104	105	0.016	P61	5+607.903	200	0.057
P30	2+211.296	85	0.010	P62	5+740.644	130	0.024
P31	2+492.090	85	0.010	P63	5+746.475	200	0.057
P32	2+640.237	85	0.010	P64	6+010.340	200	0.057
P33	2+724.489	85	0.010	P65	6+015.725	110	0.017
P34	2+734.389	85	0.010	P66	6+294.024	200	0.057
P35	2+755.413	110	0.017	P68	6+445.036	90	0.011
P36	3+115.249	110	0.017	P69	6+648.429	300	0.127
P37	3+219.451	85	0.010	P70	6+775.775	110	0.017
P38	3+254.806	105	0.016	P71	6+826.470	130	0.024
P39	3+324.462	85	0.010	P72	6+922.725	300	0.127
P41	3+419.111	85	0.010	P74	7+094.926	85	0.010
P42	3+550.937	125	0.022	P75	7+189.440	110	0.017
P43	3+819.341	110	0.017	P76	7+330.529	110	0.017
P44	4+170.946	110	0.017	P77	7+393.330	110	0.017
P45	4+329.300	110	0.017	P78	7+575.544	110	0.017
P46	4+393.253	110	0.017	P79	7+660.973	110	0.017
P47	4+476.883	125	0.022	P80	7+732.001	110	0.017
P48	4+686.657	110	0.017	P81	7+844.433	110	0.017
P49	4+706.905	105	0.016	P82	7+945.947	110	0.017
P50	4+857.478	125	0.022	P84	8+263.038	110	0.017
P51	4+905.561	110	0.017	P85	8+298.379	110	0.017

P52	4+942.330	120	0.020	P86	8+314.932	63	0.006
P53	4+989.021	105	0.016	P87	8+443.730	110	0.017
P54	5+030.890	125	0.022	P88	8+451.346	110	0.017
P55	5+077.117	110	0.017	P89	8+514.417	110	0.017
				Total			1.410

3.3 Motor pump discharges

The motor pumps inventoried along the head reach withdraw water through pipework whose diameter was measured in the field.

They fall into three categories defined by their maximum discharge, ranging from 0.01 to 0.05 m³/s. Category 1, fitted with 85-mm-diameter pipework, delivers at most 0.01 m³/s, i.e., 35 m³/h. Category 2, with a diameter of 110 mm, reaches 0.017 m³/s, i.e., about 1,050 L/min. Category 3, with a diameter of 200 mm, peaks at 0.05 m³/s, i.e., 3,000 L/min. The technical specifications were displayed on most units. For category 3, which had no nameplate, they were obtained from suppliers and a few farmers. As the maximum discharge stated for this category ranges from 2,000 to 3,000 L/min, the upper value of 3,000 L/min was adopted.

Table 2: Points equipped with motor pumps — chainage (PK), diameter, and withdrawn discharge

No.	PK	Ø (mm)	Q (m ³ /s)	No.	PK	Ø (mm)	Q (m ³ /s)
P01	0+000.000	110	0.017	P19	1+062.185	85	0.010
P02	0+115.017	110	0.017	P20	1+108.714	85	0.010
P03	0+182.047	85	0.010	P21	1+137.350	85	0.010
P06	0+308.194	110	0.017	P22	1+247.008	85	0.010
P07	0+376.224	110	0.017	P23	1+684.516	85	0.010
P08	0+395.091	85	0.010	P24	1+770.312	85	0.010
P09	0+440.709	85	0.010	P25	1+900.485	85	0.010
P10	0+474.250	85	0.010	P26	2+077.304	85	0.010
P12	0+515.067	85	0.010	P27	2+116.420	85	0.010
P14	0+616.147	110	0.017	P40	3+395.680	110	0.017
P15	0+641.642	85	0.010	P67	6+372.668	110	0.017
P16	0+669.820	85	0.010	P73	6+932.725	110	0.017
P17	0+732.470	85	0.010	P83	8+179.408	200	0.057
P18	1+023.236	85	0.010	Total			0.373

3.4 Withdrawal balance and equivalent area

The exhaustive inventory of the head reach recorded 89 unauthorized offtakes over 8.514 km, i.e., a density of 10.5 offtakes per kilometer: 62 gravity pipe connections and 27 motor pumps. The 110-mm diameter predominates (36 offtakes), followed by the 85-mm diameter (28 offtakes); the 200- and 300-mm pipes, although few in number (8 offtakes), weigh heavily in the balance.

The total withdrawn discharge reaches 1.783 m³/s, of which 1.410 m³/s is withdrawn by gravity pipes (79%) and 0.373 m³/s by motor pumps (21%). Relative to the nominal wet-season discharge of the main canal (10.878 m³/s), this withdrawal represents 16.4% of the conveyed flow and leaves only 9.095 m³/s at the entrance to the distribution network.

Since the average modulated discharge of an OPIB secondary canal is 171.5 L/s for an average command area of 53.3 ha, the withdrawal is equivalent to $1.783/0.1715 = 10.4$ secondary canals permanently diverted, i.e., 554 ha that could

be irrigated with the abstracted volume: 20% of the net area cropped in the wet season (2,772 ha) and 36% of the area that can be cropped in the dry season (1,540 ha).

This value corresponds to the installed withdrawal capacity, mobilized when all installations operate simultaneously, a situation observed in the dry season. In the wet season, gravity pipes withdraw water continuously, whereas motor pumps operate only 5 hours per day on average according to the interviews: the daily abstracted volume is then $1.410 \times 86,400 + 0.373 \times 18,000 = 128,538 \text{ m}^3/\text{d}$, i.e., a daily mean of $1.49 \text{ m}^3/\text{s}$.

Since the 554 equivalent hectares are not declared, no fees are collected on them. With a water fee of 42,000 FCFA/ha in the wet season and 14,000 FCFA/ha in the dry season, and assuming the planned dry-season cropping intensity of 50%, the annual revenue shortfall amounts to $(554 \times 42,000) + (277 \times 14,000) = 27.1$ million FCFA, within a range of 23.3 million (wet season only) to 31.0 million FCFA (dry season over the entire equivalent area). This loss is purely financial: it includes neither the loss of agricultural output nor the opportunity cost of water for regular downstream users.

Table 3: Summary of unauthorized withdrawals along the head reach of the main canal

Indicator	Unit	Value
Length surveyed	km	8.514
Total number of unauthorized offtakes	offtakes	89
Offtake density	offtakes/km	10.5
Gravity pipes / motor pumps	offtakes	62 / 27
Most frequent diameter ($\varnothing$ 110 mm)	offtakes	36
Main canal discharge (wet season)	m^3/s	10.878
Withdrawn discharge — pipes / motor pumps	m^3/s	1.410 / 0.373
Total withdrawn discharge	m^3/s	1.783
Remaining available discharge	m^3/s	9.095
Share of canal discharge withdrawn	%	16.4
Equivalent number of secondary canals	canals	10.4
Equivalent area abstracted	ha	554
Daily volume in the wet season	m^3/d	128,538
Annual water fee not collected	FCFA	27,146,000

This result is based on a discharge coefficient $\alpha = 0.6$. With the upper bound of the commonly accepted range, $\alpha = 0.8$, the withdrawal would reach $2.377 \text{ m}^3/\text{s}$, i.e., 21.9% of the discharge: the withdrawal therefore lies between 1.78 and $2.38 \text{ m}^3/\text{s}$, i.e., between 16% and 22% of the conveyed flow, the lower bound already being considerable. Finally, it adds to the technical losses of the reach: the conveyance efficiency of the lined head reach, estimated at 0.85 (3,8), does not include these withdrawals. When they are included, the actual efficiency drops to $0.85 \times (1 - 0.164) \approx 0.71$. Unauthorized offtakes thus represent a loss of the same order of magnitude as seepage, evaporation, and structural leakage combined, and more than double the total loss along the head reach.

3.5 Comparison with other irrigation schemes

Studies of network losses rarely isolate the share attributable to unauthorized withdrawals. Sibale et al. (15) are an exception: for the Bontanga scheme in Ghana, they quantified them at 1.05% of the volume entering the main canal, with technical losses of 14.4%. Technical losses are thus comparable to those of the OPIB head reach (15%), but unauthorized withdrawals are more than fifteen times higher here (16.4%), and still 13.7% in terms of daily mean discharge. The cause, however, is the same: irrigation of neighboring land located outside the scheme. The difference lies in the mode of withdrawal: at Bontanga, all withdrawals are made by motor pumps, with limited cost and operating time; along the OPIB head reach, 79% of the flow passes through gravity pipes that flow continuously at no cost.

At the Office du Niger, Mali's largest irrigation scheme, Vandersypen et al. (16) showed that even the official water user organizations rarely function, with decisions governed by informal arrangements rather than by the prescribed rules

and sanctions. The OPIB head reach is in an even less favorable situation: it has no allocated users, no user organization, and no rules to enforce. And since it serves no irrigation block, any withdrawal occurring there is entirely taken away from downstream users.

3.6 Determinants of unauthorized withdrawals

The distribution of offtakes along the canal follows two distinct patterns. Motor pumps are concentrated upstream: 23 of the 27 units, i.e., 85%, are installed between PK 0 and PK 2.2, near Bamako, where peri-urban vegetable farming is profitable and equipment is quickly paid off. However, they account for only 21% of the withdrawal. Large-diameter gravity connections, by contrast, are concentrated between PK 5 and PK 7.5: this section contains only one third of the installations but 47% of the withdrawn discharge, because the canal water level there sufficiently overlooks the adjacent land for a simple pipe through the embankment to suffice, with neither pump nor supervision. The number of offtakes points upstream; the volume withdrawn points downstream.

The interviews with twenty farmers highlighted four factors. First, the head reach serves no irrigation block: it has no allocated users, no user committee, and no water bailiff (*aiguadier*), and the withdrawal harms no visible party, only downstream users located several kilometers away. Second, the plots supplied by these connections are private properties located outside the developed scheme and generally held under registered land title: their owners therefore enjoy full land tenure security but no water right, since OPIB allocates water only to the farmers of its irrigation blocks and no procedure allows a riparian landowner to subscribe to a water fee. Here, the unauthorized connection is not the act of precarious occupants but the only means of access to water for holders of recognized land rights, which also explains the scale of the investments made, up to 200- and 300-mm pipes. Third, a 110-mm connection costs a few tens of thousands of CFA francs as a one-off expense, compared with 42,000 FCFA/ha per year for the official water fee, and the 8.5-km reach is only occasionally monitored. Finally, the age of the installations reflects *de facto* tolerance, comparable to the informal arrangements that, at the Office du Niger, coexist with and often supersede official rules (16).

Limitations of the study

The discharge coefficient was taken as uniform and equal to 0.6 for all pipes, although it varies slightly with the inlet geometry and length specific to each structure. The head H was assumed to be uniform along the head reach, in the absence of a level survey of the offtakes. Finally, summing the individual discharges assumes that all installations operate simultaneously, which corresponds to periods of high demand. These choices, based on well-established hydraulic relationships and on the measured characteristics of each installation, make it possible to establish a reliable order of magnitude of the volumes abstracted from the main canal.

4 CONCLUSION

This study identified and quantified, installation by installation, the unauthorized withdrawals along the head reach of the OPIB main canal. The exhaustive inventory of the 8.514 km of the reach recorded 89 unauthorized offtakes, including 62 gravity pipe connections and 27 motor pumps. Their total discharge is estimated at $1.783 \text{ m}^3/\text{s}$, i.e., 16.4% of the main canal discharge in the wet season, and between 16% and 22% depending on the discharge coefficient adopted. This volume is equivalent to 10.4 secondary canals and 554 irrigable hectares, i.e., 20% of the net area cropped in the wet season. It reduces the actual efficiency of the head reach from 0.85 to 0.71 and represents for OPIB a water-fee revenue shortfall of about 27 million FCFA per year.

These withdrawals are not randomly distributed. Gravity pipes, which flow continuously and at no cost, account for 79% of the withdrawn discharge, and the section between PK 5 and PK 7.5 alone concentrates 47% of it. They are made by titled riparian landowners settled outside the developed scheme, who enjoy land tenure security but no recognized water right. The phenomenon is therefore less a matter of fraud than of a regulatory gap, aggravated by the absence of users and monitoring along a reach that serves no irrigation block. Its magnitude, more than fifteen times that observed on the main canal of the Bontanga scheme in Ghana, makes it a management priority. In the dry season, when the available discharge decreases and water demand is highest, the same withdrawal would weigh even more heavily on downstream water delivery.

Recommendations

In light of these results, five measures are recommended, in order of priority:

- Address, as a priority, the 200- and 300-mm pipes located between PK 5 and PK 7.5: fewer than ten structures account for nearly half of the withdrawn discharge.

- Inventory and regularize the farmers established along the head reach, who can be identified through their land titles, by subjecting them to a water fee calculated according to the type of withdrawal, the offtake diameter, and the irrigated area.
- Equip the offtakes that are retained with calibrated, adjustable structures, rather than simple plugs, in order to control and measure the withdrawn discharge; offtakes that threaten the safety of the canal would be removed.
- Ensure regular monitoring of the reach by assigning a staff member to the head reach and periodically updating the georeferenced inventory established by this study, in order to prevent new installations.
- Establish a consultation framework between OPIB, the head-reach farmers, and Énergie du Mali (EDM), which operates the Sotuba intake structure, to integrate these withdrawals into the scheduling of diverted discharges. This framework would also serve to inform farmers of the consequences of unauthorized withdrawals for downstream users and of the conditions for their regularization.

Finally, several follow-up studies would help refine these estimates: a level survey of the offtakes to measure the available head, direct flow gauging to validate the calculated discharges, measurement of the canal discharge in the dry season, and extension of the inventory to the entire OPIB network.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

The authors thank the Baguinéda Irrigated Perimeter Office (OPIB) for granting access to the main canal and its technical archives, the riparian farmers for their availability during the interviews, and the researchers who contributed to data collection and to proofreading the manuscript. They also thank the Doctoral School of Sciences and Technologies of Mali (EDSTM) and the Teacher Training School for Technical and Vocational Education (ENETP) for their scientific supervision and institutional support.

Disclosure of conflict of interest

The authors declare no financial or personal conflict of interest that could have influenced the work reported in this article.

Statement of ethical approval

This study was conducted with the authorization of the Baguinéda Irrigated Perimeter Office (OPIB), which granted access to the head reach of the main canal, the georeferencing of the installations, and consultation of its technical archives.

Statement of informed consent

The twenty farmers interviewed were informed of the academic purpose of the survey and gave their free and informed consent; no personally identifiable data were collected, and the results are presented in aggregate form, with no monitoring or enforcement purpose.

REFERENCES

- [1] Food and Agriculture Organization of the United Nations. L'irrigation en Afrique en chiffres : enquête AQUASTAT – 2005 [Irrigation in Africa in figures: AQUASTAT survey – 2005]. Rapport sur l'eau no. 29. Rome: FAO; 2005. 96 p.
- [2] Programme National d'Irrigation de Proximité [National Small-Scale Irrigation Programme] [Internet]. [cited 2026 Mar 25]. Available from: <https://faolex.fao.org/docs/pdf/mli151455.pdf>
- [3] Office du Périmètre Irrigué de Baguinéda (OPIB), BETICO, AHT International GmbH Management and Engineering. Manuel de gestion d'eau d'irrigation [Irrigation water management manual]. 2009.
- [4] Namara RE, Sally H, editors. Proceedings of the Workshop on Irrigation in West Africa: Current Status and a View to the Future; 2010 Dec 1–2; Ouagadougou, Burkina Faso. Colombo: International Water Management Institute (IWMI); 2014. 378 p.
- [5] Office du Périmètre Irrigué de Baguinéda (OPIB), Société d'Engineering et d'Études (SEE). Études d'actualisation relatives au recalibrage et au revêtement des canaux primaires de Baguinéda et à la remise en état des ouvrages connexes [Updating studies for the reshaping and lining of the Baguinéda primary canals and the rehabilitation of related structures] [Technical report]. Baguinéda: OPIB; 2014. 51 p.

- [6] Burt CM, Styles SW. Modern Water Control and Management Practices in Irrigation: Impact on Performance. Rome: Food and Agriculture Organization (FAO); 1999.
- [7] Rutabara H. La perception de l'entretien du réseau de drainage et sa solution selon les agriculteurs : étude de cas de Baguinéda Amont (OPIB/Mali) [Farmers' perception of drainage network maintenance and its solutions: a case study of Upper Baguinéda (OPIB/Mali)]. 2016. 119 p.
- [8] Office du Périmètre Irrigué de Baguinéda (OPIB), Groupement AFRICONSULT-GID. Études APD du revêtement des canaux secondaires, de pompage d'appoint et de station d'exhaure [Detailed design studies for the lining of secondary canals, supplementary pumping, and a lift station] [Technical study]. Baguinéda: Ministère de l'Agriculture/OPIB; 2014. 82 p.
- [9] Bos MG. Design of Irrigation Systems. Wageningen: ILRI; 1994.
- [10] Burt CM, Styles SW. Modern Water Control and Management Practices in Irrigation. California: USDA Irrigation Training and Research Center; 1999.
- [11] Food and Agriculture Organization. Irrigation Water Management: Introduction to Irrigation. Rome: FAO; 1992. (Training Manual No. 1).
- [12] Bos MG. Discharge measurement structures. 3rd revised edition. Wageningen, The Netherlands: International Institute for Land Reclamation and Improvement (ILRI); 1989. (ILRI Publication 20).
- [13] U.S. Bureau of Reclamation. Water measurement manual: a water resources technical publication. 3rd edition, revised reprint. Washington, DC: U.S. Department of the Interior, Bureau of Reclamation; U.S. Government Printing Office; 2001.
- [14] Hoseini P, Vatankhah AR. Stage-discharge relationship for slide gates installed in partially full pipes. Flow Measurement and Instrumentation. 2021;77:101838. doi:10.1016/j.flowmeasinst.2020.101838
- [15] Sibale D, Kranjac-Berisavljevic G, Abdul-Ganiyu S, Mlewa R, Malinda E, Kamwendo P, et al. Assessment of water losses and projection of their impact on water demand. Applied Water Science. 2025;16:24. doi:10.1007/s13201-025-02687-9
- [16] Vandersypen K, Keita ACT, Coulibaly Y, Raes D, Jamin JY. Formal and informal decision making on water management at the village level: A case study from the Office du Niger irrigation scheme (Mali). Water Resources Research. 2007;43. doi:10.1029/2006WR005132

APPENDIX 1: SELECTED IMAGES OF UNAUTHORIZED OFFTAKES



Figure 2: Satellite image of unauthorized offtakes downstream of the third bridge of Bamako



Figure 3: Pipe



Figure 4: Motor pump

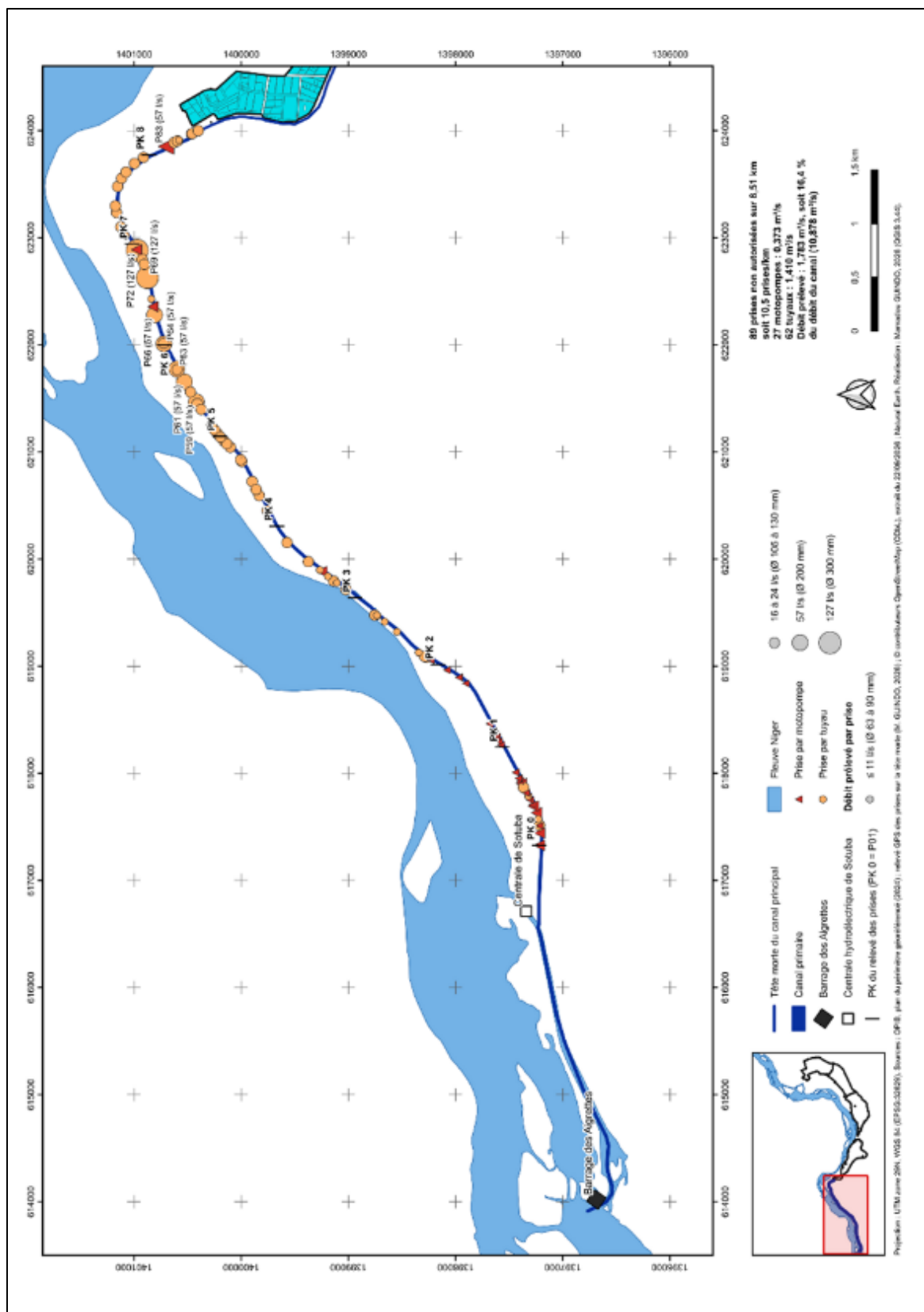


Figure 5: Location map of the unauthorized offtakes along the head reach of the main canal (PK 0 to PK 8)