Using a Micro-Hydro Power Local Plant for Providing Energy to The Irrigation System of a Sugar Cane Plantation at the District of Magude-Mozambique

Luís Pontes
luis.pontes@tecnico.ulisboa.pt
Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

***Abstract*—Sugar cane comprises on average 20% of Mozambique's total agriculture exports [1]. Benefiting from trade agreements with the EU, its exploration is a lucrative activity for the Mozambican sugar industry and has been the driving force behind the conversion of farmland into irrigated plantations under the scope of small scale irrigation projects (SSIPs). Sugar cane plantations are usually explored by local companies, but are at times, managed by smallholders associations in grant or loan schemes. Although Mozambique's climate is extremely favorable for sugar cane exploration, irrigation by pumping water from a nearby source is still required to ensure adequate crop yield. Understanding how water requirements are dependent on type of crop, agricultural practices and local climate variability, allows for an adequate design of irrigation systems and for the estimation of energy consumption. Pumping water for irrigation is an energy intensive activity with significant costs for farmers, so there is a motivation for a self-supply system, based on renewable energy, capable of powering the irrigation system. In the present case, the proximity of the Incomati river suggests the installation of a local micro-hydro power plant by evaluating the producible energy for the site in question and comparing it with the energy required for irrigation. Two distinct scenarios are considered and their technical and economical feasibility evaluated. Based in the results obtained, a derivation in the river is found to be the only moderately cost-effective solution.**

***Index Terms*—Water Requirements, Efficient Irrigation, Micro-Hydro Power Plant, Kaplan Turbine, Energetic Autonomy**

I. INTRODUCTION

SUGAR cane is a water intensive crop, with water requirements highly dependent on climate variability. Since the goal of this work is to study the prospect of installing a micro-hydro power plant in the nearby Incomati river to provide energy for a sugar cane plantation, more than determining the producible energy that would be available with this approach, one has to ask what the current energy requirements incurring from irrigation are. Thus, in the absence of energy bills, the first step should be to estimate energy consumption from water requirements. Annual water requirements are known, and although this works as a baseline scenario, in order to properly size the power plant for the application desired, assuming that is possible anyway, one has to consider how water requirements, and in turn energy consumption varies with climate. With this approach, not only can irrigation make a more efficient use of water, and thus energy, by optimizing irrigation cycles duration and frequency in response to local climate, but also, provide technical constraints, peak consumption for a given month for example, that determine the type of solution to be adopted. That is to say, if it is possible to have an isolated system, what kind of storage capability, both in terms or water (however limited) and electricity (batteries), would be needed to ensure supply and/or avoid waste if microgeneration is not possible or storage turns out to be impractical, since the power plant would potentially work continuously for 24 hours a day and irrigation cycles are discrete. Therefore, in the following, the determination of energy requirements, estimated from irrigation, considers both the original scenario (annual value) and the constructed scenario which differentiates between virgin and ratoon sugar cane, based in the FAO Penman-Monteith method, that with the available and/or estimated data, uses a finer time step to better accounting for climate variability.

As for the estimation of producible energy, an evaluation of the hydro potential, based in river flows and site characteristics is performed in order to assess the feasibility of installing a micro-hydro local power plant capable of replacing or augmenting the existing energy source powering the irrigation system. Site constraints point to a run-off river power plant with limited to no storage capability, equipped with a Kaplan turbine. Two distinct scenarios are considered, A and B, that posses significantly different levels of investment. In scenario A, the construction of a small dam is envisioned leading to a higher level of investment, while in scenario B, the approach consists of a derivation in the river by means of an open channel meant to limit the flow on the turbine, potentially being able to work all year with a dry season flow thus requiring a smaller investment. An economic analysis is performed for a range of possible scenarios, investments and options assumed, as to microgeneration or storage.

In conclusion, it is determined that a self-supply system is not possible given the technical constraints, and that an integration of a micro-hydro power plant is marginally economically feasible for scenario B.

II. CASE STUDY

Macuvulane I is a sugar cane plantation with a command area of 187.9 ha located in Magude, district of Maputo, Figure 1.

Figure 1: Macuvulane I layout.

The plantation is divided in 14 blocks explored for sugar cane, and although more blocks exist, they are not being explored (N.E.) or are reserved for nurseries.

A. Climate Characterization

Mozambique's climate is mostly tropical humid with two distinct seasons, a humid season (summer) starting in October and lasting till March and a dry season (winter) starting in April and ending in September [2].

1) Precipitation: Monthly average precipitation for Magude was estimated from different sources to produce a composite monthly precipitation series.

2) Temperature: The temperature series were obtained from the PVGIS-SARAH database with the EU PVGis tool.

B. Water Requirements

The methodology adopted to determine the crop water requirements is that of guide 56 of FAO [3], which provides the theoretical background to determine the reference evapotranspiration, ET_o [mm], equation 1.

$$\mathrm{ET_o} = \frac{0.408\Delta(\mathrm{R_n} - \mathrm{G}) + \gamma\frac{900}{\mathrm{T}+273}\mathrm{u_2}(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma(1 + 0.34\mathrm{u_2})} \tag{1}$$

where

$\mathrm{R_n}$: net radiation at the crop surface $[\mathrm{MJ}/(\mathrm{m}^2.\mathrm{day})]$
G : soil heat flux density $[\mathrm{MJ}/(\mathrm{m}^2.\mathrm{day})]$
T : mean daily air temperature at 2 m height [°C]
$\mathrm{u_2}$: wind speed at 2 m height [m/s]
$\mathrm{e_s}$: saturation vapour pressure [kPa]
$\mathrm{e_a}$: actual vapour pressure [kPa]
$\mathrm{e_s} - \mathrm{e_a}$: vapour pressure deficit [kPa]
γ : psychrometric constant [kPa/°C]
Δ : slope of the saturation vapour pressure temperature relationship [kPa/°C]

For absent data, the guide provides methods for estimating required parameters. The $\mathrm{ET_o}$ is then corrected with a crop coefficient K_c, that incorporates data about the crop, agricultural and irrigation practices, etc, to yield the desired crop evapotranspiration ET_c [mm].

With respect to agricultural practices, assumptions had to be made, for example the starting month was assumed to be June. In regard to the type of crop, there are two possibilities to consider, virgin sugar cane and ratoon sugar cane. Virgin crop is the first crop planted, followed by one or more (at least two and up to eight in some cases) ratoon crops. The practice of ratoon refers to leaving the root and a portion of the plant above ground for the next crop cycle. Different calibration for the crop coefficient K_c, is required for each agricultural practice as they possess very different lengths of growth stages.

With the crop evapotranspiration computed, some adjustments concerning the uneven distribution of water associated with the method of irrigation (sprinkler) are performed and the final water requirements estimated.

1) Effective Precipitation: The effective precipitation $\mathrm{P_e}$ can be estimated based on [4], equation 2.

$$\mathrm{P_e} = \mathrm{SF}\big(0.70917\mathrm{P_t^{0.82416}} - 0.11556\big)\big(10^{0.02426\,\mathrm{ET_c}}\big) \tag{2}$$

where

$\mathrm{P_e}$: average monthly effective precipitation [in]
$\mathrm{P_t}$: monthly mean precipitation [in]
$\mathrm{ET_c}$: average monthly crop evapotranspiration [in]
SF : soil water storage factor

with the soil water storage factor defined by equation 3

$$\mathrm{SF} = (0.531747 + 0.295164\,\mathrm{D} - 0.057697\,\mathrm{D}^2 + 0.003804\,\mathrm{D}^3) \tag{3}$$

where D [in] is the usable water soil storage.

2) Net Irrigation Requirements: The net irrigation requirements, I_N [mm] are computed from equation 4

$$\mathrm{I}_N = \mathrm{ET_c} - \mathrm{P}_e \tag{4}$$

3) Gross Irrigation Requirements: Finally, the net irrigation requirements I_N [mm] are adjusted by applying a uniformity coefficient $\mathrm{K_u}$, here assumed to be $\mathrm{K_u} = 0.9$, after which the resulting value is increased by 10% to account for losses and other water usage, yielding the gross water requirements I_G [mm], equation 5.

$$\mathrm{I}_G = 1.1\frac{\mathrm{I}_N}{\mathrm{K_u}} \tag{5}$$

Water requirement results for virgin and ratoon sugar cane are presented in Tables I and II, respectively.

Table I: Virgin sugar cane water requirements.

Month	ET_o [mm]	K_c	ET_c [mm]	P_t [mm]	P_e [mm]	I_N [mm]	I_G [mm]
Jun	77.2	0.7250	55.9	16.5	10.1	45.9	56.1
Jul	85.3	0.7500	63.9	16.2	10.1	53.9	65.8
Aug	107.8	0.9375	101.1	14.5	9.7	91.4	111.8
Sep	129.7	1.1500	149.2	33.3	25.0	124.1	151.8
Oct	145.6	1.2500	181.9	51.6	40.4	141.6	173.1
Nov	144.6	1.2500	180.7	74.4	55.9	124.8	152.6
Dec	150.3	1.2500	187.9	86.7	64.9	122.9	150.3
Jan	137.3	1.2500	171.6	146.8	98.8	72.8	88.9
Feb	126.1	1.2500	157.6	134.1	88.7	68.9	84.2
Mar	117.6	1.2500	147.1	87.5	59.8	87.2	106.6
Apr	90.9	1.2500	113.6	51.2	34.5	79.1	96.8
May	86.1	1.2033	103.6	26.7	18.3	85.3	104.2
Jun	77.2	1.0917	84.3	16.5	10.7	73.6	89.9
Jul	85.3	1.0000	85.3	16.2	10.6	74.7	91.3
Aug	107.8	0.9000	97.0	14.5	9.6	87.5	106.9
Sep	99.4	0.8000	79.6	33.3	21.5	58.1	70.9
Total	1768.2	–	1960.4	819.6	568.5	1391.8	1701.1

Table II: Ratoon sugar cane water requirements.

Month	ET_o [mm]	K_c	ET_c [mm]	P_t [mm]	P_e [mm]	I_N [mm]	I_G [mm]
Jun	77.2	0.7250	55.9	16.5	10.1	45.9	56.1
Jul	85.3	0.8750	74.6	16.2	10.3	64.3	78.6
Aug	107.8	1.1758	126.8	14.5	10.2	116.6	142.5
Sep	129.7	1.2500	162.1	33.3	25.8	136.4	166.7
Oct	145.6	1.2500	181.9	51.6	40.4	141.6	173.1
Nov	144.6	1.2500	180.7	74.4	55.9	124.8	152.6
Dec	150.3	1.2500	187.9	86.7	64.9	122.9	150.3
Jan	137.3	1.2500	171.6	146.8	98.8	72.8	88.9
Feb	126.1	1.2143	153.1	134.1	87.8	65.3	79.8
Mar	117.6	0.9792	115.2	87.5	55.8	59.4	72.6
Apr	48.5	0.8125	39.4	51.2	29.3	10.1	12.3
Total	1269.9	–	1449.3	712.5	489.3	960.1	1173.4

Figure 2 shows how irrigation lags precipitation during the most demanding months, potentially suggesting that in theory the peak demand, both in terms of water and energy, could be reduced by delaying plantation by 2 or 3 months.

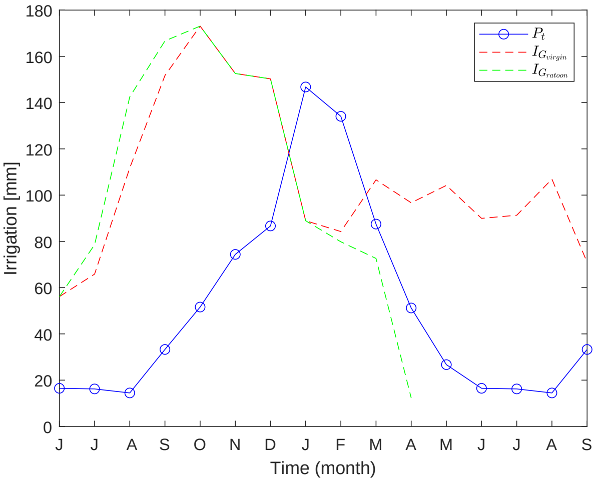

Figure 2: Gross irrigation requirements vs precipitation.

C. Irrigation System

The design duty of the pumps, Q_p and the nominal power of the motors, P are summarized in Table III.

Table III: Characteristics of installed units.

Unit	Q_p [l/s]	P [kW]
1	97.2	90
2	97.2	90
3	207.0	132
Total	401.4	312

Due to unknown issues, group 3 is disabled but throughout this work both possibilities (2 or 3 pumps) will be considered.

1) Pump Operation: The hydraulic power P [W] of a turbomachine depends on its design flow Q [m^3/s], the head pressure it needs to overcome H [m], the fluid specific weight, γ [N/m^3], and the overall efficiency, η, equation 6.

$$P = \frac{\gamma Q H}{\eta} \tag{6}$$

The H-Q curves could not be obtained from local inspection, but Figure 3 intends to show the qualitative behavior of the system.

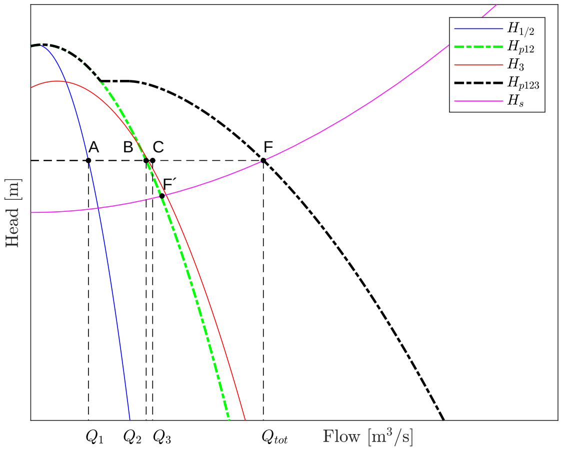

Figure 3: Example of parallel association of pumps.

In general, the curve that describes the change in head H [m] of the pump with the flow, Q [m^3/s] is given by equation 7.

$$H = A + B\,Q - C\,Q^2 \tag{7}$$

As for the system, it is represented by a type of curve like H_s (pink), equation 8.

$$H_s = A + B\,Q^2 \tag{8}$$

While the real shape of the curves is unknown, from Table III and knowing the design operating pressure $P_d = 600\,\text{kPa}$, points A (0.097, 61,19), C (0.207, 61,19) and the operating point F (0.401,61,19), are known. With only 2 pumps, the operating point moves to F'. One advantage of the parallel association is that the flow can be adjusted by connecting or disconnecting units from operation without compromising the overall system.

As the head can be maintained by the remaining units, since $H_{\text{tot}} = H_1 = H_2 = H_3$, and the flow $Q_{\text{tot}} = Q_1 + Q_2 + Q_3$, a parallel configuration provides a greater flexibility, and redundancy allowing the system to maintain its operation with just 2 units.

2) Required Work Hours: Considering the command area, A = 187.9 ha, and the design duty of the pumps Q_p^i [l/s], where i is the number of working pumps, the water duty per hectare, $\mathrm{W}_i^{'}$ [$\mathrm{m^3\,hr^{-1}\,ha^{-1}}$] is given by equation 9:

$$\mathrm{W}_i^{'} = \frac{Q_p^i}{\mathrm{A}} \times \frac{3600}{10^3},\ i = \{2, 3\} \tag{9}$$

For the original scenario, with $\mathrm{I}_N^{0'} = 13\,660\,\mathrm{m^3\,ha^{-1}\,year^{-1}}$, the estimated annual work hours of the pumps, T_i^0 [hr], can be determined by equation 10.

$$T_i^0 = \frac{\mathrm{I}_N^{0'}}{W_i^{'}},\ i = \{2, 3\} \tag{10}$$

Table IV: Water duty and annual work hours.

Pumps	Q_p^i [l/s]	W_i [$\mathrm{l\,s^{-1}\,ha^{-1}}$]	$\mathrm{W}_i^{'}$ [$\mathrm{m^3\,hr^{-1}\,ha^{-1}}$]	T_i^0 [hr]
2	194.4	1.0346	3.7245	3667.6
3	401.4	2.1300	7.6680	1776.8

Under the constructed scenario, Table V presents the work hours for different pump arrangements $\mathrm{T}_i^{v/r}$ [hr], required to deliver the computed gross irrigation requirements $\mathrm{I}_G^{v/r}$ [mm], as defined by equation 11.

$$\mathrm{T}_i{}^{v/r} = 10 \times \frac{\mathrm{I}_G^{v/r}}{\mathrm{W}_i^{'}},\ i = \{2, 3\} \tag{11}$$

Table V: Required pump working hours.

	Virgin Cane		Ratoon Cane	
Month	T_2^v [hr]	T_3^v [hr]	T_2^r [hr]	T_3^r [hr]
Jun	151	73	151	73
Jul	177	86	211	102
Aug	300	145	383	185
Sept	407	197	448	217
Oct	465	225	465	225
Nov	410	198	410	198
Dec	403	195	403	195
Jan	239	116	239	116
Feb	226	110	214	104
Mar	286	139	195	94
Apr	260	126	33	16
May	280	135	–	–
Jun	242	116	–	–
Jul	245	119	–	–
Aug	287	139	–	–
Sept	191	92	–	–
Total	1701.1	2212	3151	1526

3) Required Units: For some months, 1 or 2 pumps are not enough to ensure $\mathrm{I}_G^{v/r}$ [mm]. Thus the solution that can guarantee adequate irrigation is that of Table VI.

Table VI: Required number of units.

	Virgin Cane			Ratoon Cane		
Month	#P	#P	#P	#P	#P	#P
Jun	1	2	3	1	2	3
Jul	1	2	3	-	2	3
Aug	-	2	3	-	-	3
Sep	-	-	3	-	-	3
Oct	-	-	3	-	-	3
Nov	-	-	3	-	-	3
Dec	-	-	3	-	-	3
Jan	-	2	3	-	2	3
Feb	-	2	3	-	2	3
Mar	-	2	3	-	2	3
Apr	-	2	3	1	2	3
May	-	2	3	–	–	–
Jun	-	2	3	–	–	–
Jul	-	2	3	–	–	–
Aug	-	2	3	–	–	–
Sep	-	2	3	–	–	–

4) Energy Consumption: The motivation behind the previous sections was so that consumption could be indirectly estimated from the installed capacity of the motors and the frequency of irrigation. Under the original scenario, E_i^o [MWh] is given by equation 12, with results in Table VII.

$$\mathrm{E}_i^o = P_i \times \mathrm{T}_i^0,\ i = \{2, 3\} \tag{12}$$

Table VII: Energy consumption (original scenario).

Pumps	P_i [kW]	T_i^0 [hr]	E_i^0 [MWh]
2	180	3667.6	660.17
3	312	1776.8	554.36

For the constructed scenario, equation 13 yields the results presented in Table VIII.

$$E_i^{v/r} = P_i\, T_i^{v/r},\ i = \{2, 3\} \tag{13}$$

Table VIII: Energy consumption (constructed scenario).

	Virgin Cane		Ratoon Cane	
Month	E_2^v [MWh]	E_3^v [MWh]	E_2^r [MWh]	E_3^r [MWh]
Jun	27.12	22.77	27.12	22.77
Jul	31.82	26.71	37.97	31.88
Aug	54.01	45.34	68.85	57.80
Sep	73.32	61.55	80.55	67.62
Oct	83.65	70.21	83.64	70.21
Nov	73.74	61.89	73.74	61.89
Dec	72.62	60.96	72.62	60.96
Jan	42.97	36.07	42.87	36.07
Feb	40.72	34.18	38.57	32.38
Mar	51.52	43.25	35.09	29.46
Apr	46.73	39.23	5.95	4.99
May	50.36	42.27	–	–
Jun	43.47	36.49	–	–
Jul	44.12	37.04	–	–
Aug	51.67	43.37	–	–
Sep	34.30	28.79	–	–
Total	822.12	690.14	567.08	476.05

5) Energy Efficiency: In theory, the 3 pumps were chosen so that the operating point F in Figure 3 also coincides with the pump's best efficient point (BEP) but since the efficiency curve is also unknown, it is not possible to determine the new operating point of a system working with 2 pumps. Therefore, the only thing that can be said is that the new operating point F' implies a decrease in efficiency. At the design duty point F, Figure 3, the combined efficiency of the units (pump + motor) can be roughly evaluated solely from P and Q, equation 14.

$$\eta = \underbrace{\frac{\gamma}{H}}_{k} \frac{Q}{P} \tag{14}$$

Thus, if it can be assumed that both the fluid (hence γ), and the head of the installation H remain constant after the loss of the larger unit, that is, which is the same as saying that the system curve H_s in Figure 3 is horizontal and that point F moves to point B instead of F', the overall decrease in efficiency is given by equation 15.

$$\Delta\eta_{3\rightarrow2} = \frac{\eta_3 - \eta_2}{\eta_3} = 1 - \frac{Q_2}{Q_3}\frac{P_3}{P_2} = 0.1597 \tag{15}$$

Alternatively, the impact on efficiency can be estimated by determining the relative decrease in energy consumption ΔE if the larger pump were to be repaired, equation 16.

$$\Delta E_{2\rightarrow3} = \frac{E_2^o - E_3^o}{E_2^o} = \frac{660.17 - 554.36}{660.17} = 0.1603 \tag{16}$$

So, the failure of the larger pump has a deleterious effect on the annual costs, since it made it so that the arrangement with the 3 working delivered a higher value of flow per unity of power.

III. SELF-SUPPLY SYSTEM

Considering the energy costs incurring from the estimated energy consumption, the need arises for alternatives that offer both a green and cheap source of energy. In this sense, a self-supply system refers to a system based in renewable energy, designed to replace an external power source, in this case the national electric grid, and thus able to generate and supply its own power [5].

A. Evaluation of Hydropower Potential

An adequate characterization of the river flow, including for the dry season and over a sufficient number of years to account for hydrological variability, as well as a topographic survey is required for an accurate project planning, namely in selecting the type of turbine that results in the best performance for the desired application.

1) Site Characterization: Detailed topographic maps were not available for this region, although a simple elevation profile from Goggle Earth helped determine that up to 100 m upstream from the pumping station the total gain of elevation is merely 0.15 m.

2) River Flow Characterization: Hydrological records produced by ARA-Sul pertaining station E-43 located in Magude, are scarce and incomplete, with data available only for the wet season that typically begins in November and ends around April. The chronological daily flow series for the period of 2018-2021, in which data is available, is shown in Figure 4.

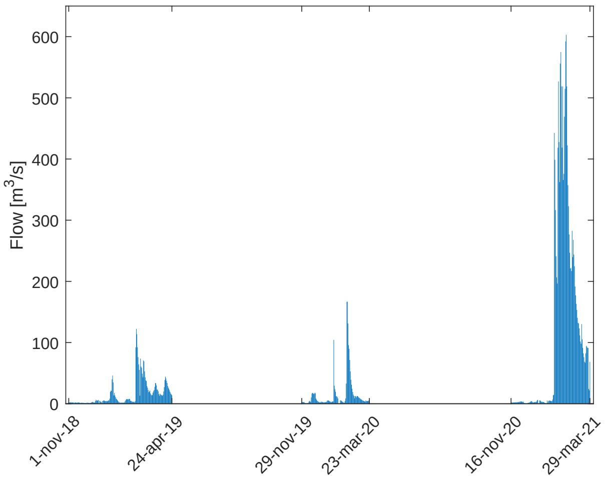

Figure 4: Recorded daily flows - 2018-2021, Magude - E43

For comparison, Table IX presents some relevant information associated with each season.

Table IX: Season data indicators.

Season	Data points	Q_{min} [m^3/s]	Q_{max} [m^3/s]	Q_{mean} [m^3/s]
18/19	173	0.94	122.25	16.03
19/20	112	0.64	166.73	14.97
20/21	132	0.17	603.12	121.56

Usually, one would work with a complete mean chronological daily flow series, but the annual series are incomplete, only records for 3 seasons are available, the starting and ending dates do not even coincide, and the 20/21 season was marked by floods. Therefore, it seemed unreasonable to work with a mean series in this context. By sorting the chronological daily flow series in a decreasing manner, one obtains the flow duration curves (FDCs), which are then modeled to estimate the producible energy. The 18/19 and 20/21 wet seasons are reasonably well modeled by a two-parameter exponential, equation (17).

$$Q(t) = ae^{-b/t} \tag{17}$$

By contrast, the flow duration curve of the 19/20 wet season is better modeled by a reciprocal function, equation (18).

$$Q(t) = a\frac{1}{t} \tag{18}$$

With the flow modeled, the determination of the modular flow Q_N [m^3/s], ensues, equation (19).

$$Q_N = \frac{\text{area under the curve}}{\text{time}} \tag{19}$$

A summary of these results is presented in Table X, where the model parameters were determined in MATLAB with the *fit* function.

Table X: Characterization of recorded flows.

Wet Season	Area	Days	Parameters	Q_N [m^3/s]
18/19	2529	173	a = 98.83; b = 27.13	14.62
19/20	1168	112	a = 247.50	10.43
20/21	16615	132	a = 686.30; b = 25.33	125.87

The first two seasons are considered to be typical seasons, and the 2020/2021 season is considered to be atypical due to a prevalence of floods.

IV. LOCAL MICRO-HYDRO POWER PLANT

By definition, a micro-hydro power plant has an installed capacity bellow 500 kW, and typically consists of several structures as Figure 5 indicates.

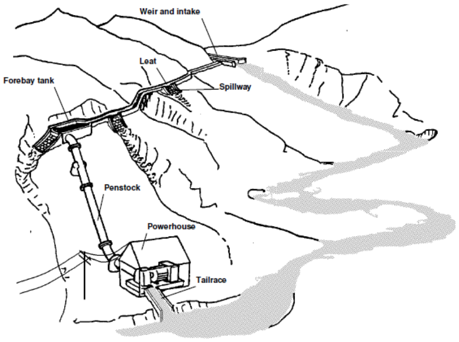

Figure 5: Typical small hydro scheme. Adapted from [6]

The exact scheme and structures required depend on site characteristics and other constraints. Hydro power plants can also be classified in accordance to their storage capacity. Power plants with reservoirs are said to be storage power plants, where as, run-off-river power plants possess limited storage if any at all, lacking the ability to regulate river flows. For low heads, two configurations are possible, as Figure 6 shows.

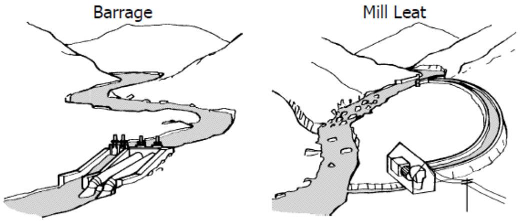

Figure 6: Low head configurations. Adapted from [6].

In the following, two scenarios, A and B, based in a run-of-river hydroplant are considered. In scenario A, the turbine is housed in a dam like structure, barrage type in Figure 6. In scenario B, a fraction of river flow is diverted through an open channel leading to the power house where the turbine is located, mill leat type in Figure 6.

A. *Mecanoelectric Equipment*

The two most important pieces of equipment in micro-hydro power plant are the turbine and the generator, whose selection depends on site characteristics.

1) Turbine Selection: The acquisition of the turbine usually represents a considerable fraction of the cost of the micro-hydro power plant, up to 50%, making it so that an adequate choice of this equipment is crucial [7]. The selection of the turbine from a technical viewpoint is essentially determined by the interaction of three parameters: flow $Q\,[\mathrm{m}^3/\mathrm{s}]$, head $H\,[\mathrm{m}]$ and installed capacity $P\,[\mathrm{kW}]$ [7].

Usually, in a pre-selection phase, the type of turbine can be determined from graphs such as the one in Figure 7.

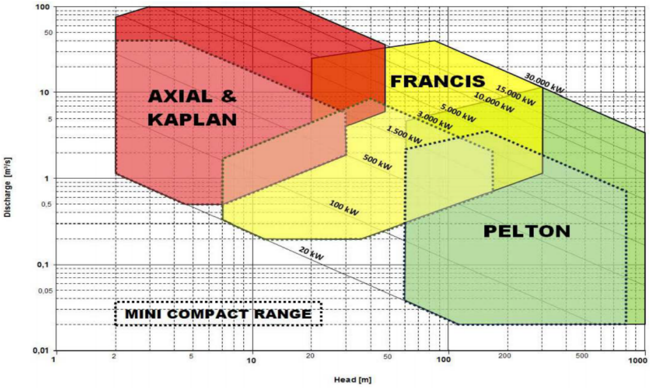

Figure 7: Turbine pre-selection. [Source: Andritz Hydro presentation, 2016 Energy Summit]

For low heads, $H_b = 2\,\mathrm{m}$, and the modular flow determined, $Q_N \simeq 10\,\mathrm{m}^3/\mathrm{s}$, Table X the choice falls on the Kaplan type with an installed capacity $P > 100\,\mathrm{kW}$.

Kaplan turbines are well suited for applications involving run-of-river hydro power plants due to their ability to maintain a nearly constant efficiency when faced with changes in flow, since a defining characteristic of this type of hydroplants is the lack of ability to regulate river flows.

The composition of a Kaplan turbine is showed in Figure 8.

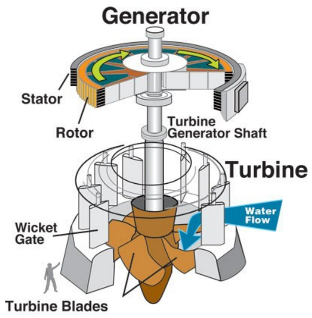

Figure 8: Kaplan turbine. [Source: https://energyeducation.ca]

Several variants of Kaplan turbines exist, but fundamentally, their control is possible by acting on the wicket gates (distributor) and/or on the blades of the rotor, Figure 9.

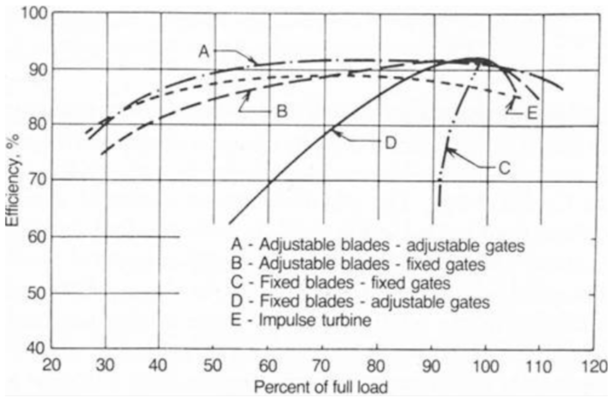

Figure 9: Efficiency curves of Kaplan variants. [Source: www.renewablesfirst.co.uk]

A Kaplan turbine with controllable blades is simplly regulated (B), or alternatively, has a regulated rotor (RR). This is critical to widen the range of operation, resulting in a flat efficiency curve. If the wicket gates are also controlled (A), the turbine has double regulation (DR). Another possibility is to control the wicket-gates and not the blades (D).

2) Generator Selection: Typically, small hydroelectric applications (< 5 MW), are equipped with induction generators, avoiding the need for the exciter, voltage regulator and synchronizer required when using alternators [8].

B. Scenario A: Barrage

A simplified model to help determine the size of the installed unit is employed, equation 20, and given the minimum gross head to ensure viable exploration of Kaplan turbines, Figure 7, and that the adjacent terrain is very smooth, it is assumed that the hydraulic head achieved after constructing the dam is $H_b = 2\,\text{m}$.

1) Installable Power: A common expression to estimate the value of P_N [kW], which depends on the nominal flow Q_N [m^3/s] and the hydraulic head H_b [m], consists on assuming a global efficiency η close to 70% while taking the specific weight of water to be $\gamma = 9.810\,\text{kN/m}^3$ [7], equation 20,

$$P_N = \gamma Q_N H_b \eta \simeq 7 Q_N H_b \tag{20}$$

Table XI summarizes these results, where the power is rounded up to the closest integer.

Table XI: Power plant installable capacity.

Season	Q_N [m^3/s]	P_N [kW]
18/19	14.62	200
19/20	10.43	150
20/21	125.87	1500

2) Estimated Producible Energy: It is common to attribute exploration limits to turbines, that define the range of operation in relation to the nominal flow in which the turbine can maintain its operation without a significant variation of its efficiency [7]. Typical exploration limits for two different control strategies of Kaplan turbines are given in Table XII.

Table XII: Exploration limits of Kaplan turbines [7].

Turbine	$\alpha_1 = Q_{min}/Q_N$	$\alpha_2 = Q_{max}/Q_N$
DR Kaplan	0.25	1.25
RR Kaplan	0.40	1.00

As an example, the exploration area of a DR Kaplan turbine for the 18/19 season is shaded in Figure 10.

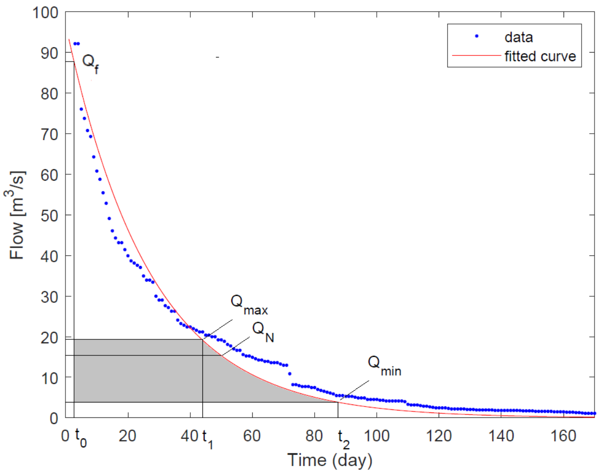

Figure 10: Exploration area using a DR Kaplan (18/19).

The values of flow Q_{min}, Q_{max} define times t_2 and t_1, respectively. The flood flow Q_f determines time t_0, estimated at 2, 3 and 44 days for each season, respectively.

Integrating equation 20, over the exploration limits of the turbine, leads to an estimate of the producible energy E [Wh], expressed by equation 21 [7], with results in Table XIII.

$$E = 7 \times H_b \times \left((t_1 - t_0)\alpha_2 Q_N + \int_{t_1}^{t_2} Q(t)\,dt \right) \times 24 \text{ [Wh]} \tag{21}$$

Table XIII: Estimated producible energy (scenario A).

Season	E_{DR} [MWh]	E_{RR} [MWh]
18/19	398.44	322.20
19/20	203.87	148.86
20/21	717.32	598.65

3) Self-Supply Condition: For the original scenario, if consumption is assumed to be equally distributed, the energy to be met is around $\bar{E}_2^0 = 55$ MWh/month and $\bar{E}_3^0 = 46$ MWh/month. For the constructed scenario, the demand peaks in October with $E_2^v = 83.65\,\text{MWh}$.

As to the producible energy in scenario A, an average monthly energy estimate, $\bar{E}\,[\mathrm{MWh/month}]$ is considered, Table XIV.

Table XIV: Estimated mean monthly energy (scenario A).

Season	Months	$\bar{E}_{DR}$ [MWh/month]	$\bar{E}_{RR}$ [MWh/month]
18/19	5.77	69.05	55.84
19/20	3.73	54.66	39.91
20/21	4.40	163.03	136.06

Thus, a DR Kaplan turbine would, at its worst, produce $\bar{E} = 54.66$ MWh/month and be able to match, on average, the monthly demand $\bar{E}_2^0 = 55$ MWh/month for the worst case. As for the constructed scenarios, on average, the demand from January to March would be satisfied, although a complete coverage for the wet season would be impossible.

C. Scenario B: Channel

One could start by asking what value of Q the channel would need to discharge so that the turbine output would match the power rating of a particular pump arrangement, $P_2 = 180\,\mathrm{kW}$ or $P_3 = 312\,\mathrm{kW}$, but from scenario A, one already knows this would never lead to an isolated system. So in this scenario, the assumption is that only one of the smaller pumps could in principle (to be verified) be shutoff from the grid.

1) Channel Design: In practice, a rectangular open channel, Figure 11, is easier and cheaper to construct and although its cross section could be optimized to minimize excavation costs, a more pragmatical solution is to pick both the width b and depth y and check if the value of the Froude number is bellow unit to ensure a subcritical flow.

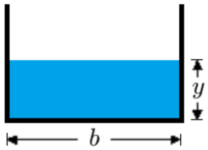

Figure 11: Channel cross section.

The cross section $A\,[\mathrm{m}^2]$ and the wetted perimeter $P\,[\mathrm{m}]$ are defined by equation 22

$$A = by \qquad P = 2y + b \tag{22}$$

The hydraulic radius $R_h\,[\mathrm{m}]$, is defined as the ratio of the cross section to the wetted perimeter, equation 23.

$$R_h = \frac{A}{P} \tag{23}$$

If the channel has slope S, and a Gauckler–Manning coefficient n, the mean velocity of the fluid $v\,[\mathrm{m/s}]$ is dictated by the Gauckler-Manning formula, equation 24

$$v = \frac{k}{n} R_h^{2/3} \sqrt{S}, \qquad k = 1 \text{ (SI units)} \tag{24}$$

The flow is given by equation 25

$$Q = vA \tag{25}$$

Combining equations 24 and 25, the flow Q, comes as

$$Q = \frac{R_h^{2/3} \sqrt{S} A}{n} \tag{26}$$

Rewriting equation 20, the flow that the channel needs to carry Q $[\mathrm{m}^3/\mathrm{s}]$, can be expressed by equation 27.

$$Q = \frac{P}{\gamma\,\eta\,h} \tag{27}$$

Thus, from equations 22, 23 and 26, Q can be expressed as a function of the channel dimensions b and h, equation 28

$$Q = \left(\frac{bh}{2h + b}\right)^{\frac{2}{3}} \frac{\sqrt{S}}{n}\, bh \tag{28}$$

Note that y is really the height of water in the channel h, and is dependent on flow. The head h as a function of the required power can be computed by substituting equation 27 in equation 28, leading to transcendental equation 29

$$\frac{P}{\gamma\,\eta\,h} - \left(\frac{bh}{bh + b}\right)^{\frac{2}{3}} \frac{\sqrt{S}}{n}\, bh = 0 \tag{29}$$

Assuming a channel made of finished concrete with a Gauckler–Manning coefficient of n = 0.012, a value of slope S = 0.001, knowing the power rating of one of the smaller pumps, P = 90 kW and fixing a value for the width of the channel, for example, b = 2 m, equation 29 leads to a height of water in the channel of h = 1.6310 m and from equation 27, $Q_{\text{channel}} \simeq 6.25\,\mathrm{m}^3/\mathrm{s}$. Since, in the dry season this requirement cannot be fulfilled, the only alternative is to use a reservoir.

2) Reservoir Loading the Channel: The reservoir function is then to load the channel so that an appropriate value of Q reaches the turbine for the duration of an irrigation cycle. The balance of water in the reservoir is given by equation 30.

$$\frac{dV(t)}{dt} = Q_{\text{in}}(t) - Q_{\text{out}}(t) \tag{30}$$

As an example, Figure 12 shows the variation of volume in the reservoir for 3 irrigation cycles.

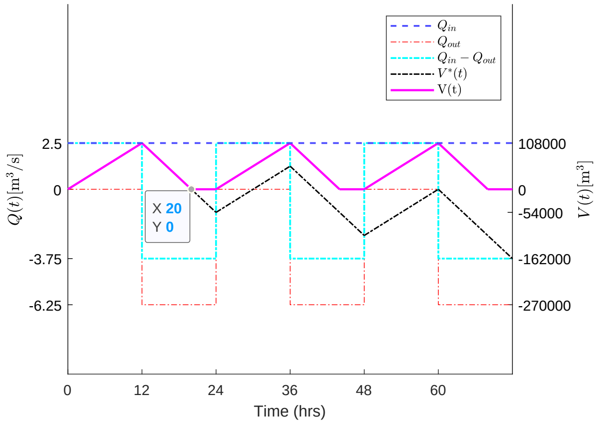

Figure 12: Volume of water in the reservoir.

The reservoir is assumed to be empty at t = 0, and continually fills at a rate of $Q_{\text{in}} = 9000\,\text{m}^3/\text{hr}$ or $2.5\,\text{m}^3/\text{s}$. The rate of discharge is $Q_{\text{out}} = 13500\,\text{m}^3/\text{hr}$ or $3.75\,\text{m}^3/\text{s}$ for the second half cycle. Then, in the first cycle, the volume in the reservoir is given by equation 31

$$V(t) = \begin{cases} 9000\,t, & 0 \leq t \leq 12 \\ -13500t + 270000, & 12 \leq t \leq 20 \end{cases} \quad [\text{m}^3] \tag{31}$$

In order to ensure a fixed length of irrigation cycles, in this case 8 hours, the reservoir exit valve must only close at the end of each half-cycle. If for example, the outflow cannot be maintained for 12 hours, since the reservoir is empty at t = 20 hours, then, one could think of closing the exit valve and let the reservoir refill, but this would lead to an oscillating behavior for $V(t)$ and as a consequence for the duration of irrigation. The black dashed line, $V^*(t)$, indicates a deficit of water that arises as a consequence of the reservoir's inability to maintain the required outflow in the channel for the duration in question. This means that as each irrigation cycle ends, the deficit of volume increases by 54 000 m^3 per day. If one irrigation cycle lasts for 6 days, then, the deficit will total 324 000 m^3 and this would need to be the initial condition, the volume of water in the reservoir for $t = 0$.

Thus given the dimensions involved, not even one pump can be isolated from the grid in this manner, as the flow of the river is not constant and during the dry season it is substantially lower than the required value.

3) Range of Turbine Operation: As the load of the machine changes, the power available at its shaft also changes, which means that, for a constant head, the machine will not always work with the maximum flow, Q_{max}. For this reason, when considering the efficiency curve of a turbine, the flow is given as a fraction of Q_{max} which is also expressed as the percentage of gate opening. The turbine exploration limits discussed in scenario A follow from this. While the efficiency curves of DR and RR turbines are flat, in reality, near the edges of the interval, the efficiency drops. For scenario B, it is convenient to assume a constant efficiency of $\eta = 90\,\%$, which means that the opening of the intake in percentage, Q/Q_{design}, has to be bounded by $\alpha'_1 = 0.4$ and $\alpha'_2 = 1$ for a DR Kaplan and by $\alpha'_1 = 0.6$ and $\alpha'_2 = 1$ for a RR Kaplan. As such, with the design flow set, the range of flows that the turbine can work with, while maintaining a constant efficiency, can be determined.

$$\alpha'_1 \leq \frac{Q}{Q_{design}} \leq \alpha'_2 \implies \eta = 90\,\% \tag{32}$$

which means that the flow in the turbine is in the range

$$\alpha'_1\, Q_{design} \leq Q \leq \alpha_2{}' Q_{design} \tag{33}$$

Then, if $Q_{design} = 2.5\,\text{m}^3/\text{s}$, the flow is inside the interval $Q \in [1,\, 2.5]\,\text{m}^3/\text{s}$ for a DR Kaplan and in the range $Q \in [1.5,\, 2.5]\,\text{m}^3/\text{s}$ for a RR Kaplan.

If the river flow exceeds Q_{design}, the channel will still carry Q_{design}. In fact, since $Q_{\text{design}} = 2.5\,\text{m}^3/\text{s}$, and the maximum channel flow is $Q_{\text{max}} = 6.25\,\text{m}^3/\text{s}$, then, in truth, the channel can carry Q_{max} if the river flow allows it, but it is assumed that a spillway exists in the channel limiting the flow to Q_{design}.

$$Q_{design} \leq Q \leq Q_{\text{max}} \implies Q = Q_{\text{design}} \tag{34}$$

A flow in the channel $Q = Q_{design}$ results in a head of water available to the turbine of $h = 0.8105\,\text{m}$, which means that the turbine size would need to be, from equation 20, rounded to $P = 20$ kW. This is the lower limit, as to installed power, for the exploration of Kaplan Turbines, Figure 7.

4) Estimated Producible Energy: With the assumption of η = 0.9, the power P [W] associated with a given value of flow $Q(i)$ in the channel is given by equation 35.

$$P(i) = \gamma\, Q(i)\, h(i)\, \eta \tag{35}$$

and since the flow $Q(i)$ is measured daily, the daily energy $E(i)$ [Wh] is computed from equation 36

$$E(i) = 24 \sum_i P(i) \tag{36}$$

Taking the 4 following assumptions, the results are presented in Table XV.

- I) energy produced in the wet season as a result of recorded flows;
- II) energy produced in the dry season, assuming a constant basic mean flow, $Q_{\text{mean}} = 2.5\,\text{m}^3/\text{s}$, where the duration of the dry season is 365 minus the duration of the wet season;
- III) annual energy as the sum of energy produced in the wet season (I) plus energy produced in the dry season (II);
- IV) annual energy produced assuming the flow in the channel is constant and equal to $Q_{\text{mean}} = 2.5\,\text{m}^3/\text{s}$ all year.

Table XV: Estimated producible energy (scenario B).

	DR Kaplan			RR Kaplan		
Season	$E(I)$ [MWh]	$E(II)$ [MWh]	$E(III)$ [MWh]	$E(I)$ [MWh]	$E(II)$ [MWh]	$E(III)$ [MWh]
18/19	63.67	82.87	146.54	62.18	88.02	150.20
19/20	44.78	109.49	154.27	44.49	110.78	155.27
20/21	50.03	103.05	153.08	49.71	104.34	154.05

Note that the energy produced in scenario IV is independent of season and type of turbine, $E(IV) = 156.72\,\text{MWh}$.

V. PROPOSED SOLUTION

Although scenario B would seem to be more realistic and result on a smaller investment, it also implies smaller energy production. Adding to that, the possibility of a microgeneration production regime shifts technical constraints associated with storage and so, the determination of the best solution, has to be based on an economic analysis.

VI. ECONOMIC ANALYSIS

A. Hydroplant Investment

Based in the installed capacity for both scenarios, and in typical unitary investment estimated for a micro hydroplant (2020), the total investment is given in Table XVI.

Table XVI: Cost investment of micro-hydro (2020).

Season	Power [kW]	min [€]	mean [€]	max [€]
18/19	200	456 000	942 000	1 850 000
19/20	150	342 000	707 000	1 388 000
-	20	45 600	94 200	185 000

The unitary mean annual cost, c [€/MWh] and the levelized cost of energy, LCOE [€/MWh] assuming a lifespan of the power plant $n = 25$ years, a discount rate $r = 0.07$, an investment made in its entirety in the initial moment, t = 0, and the maintenance and operation costs constant over the lifespan of the power plant, are given in Table XVII.

Table XVII: Mean and levelized cost of energy.

			I_t [€]	$d_{om}I_t$ [€]	E_a [MWh]		c [€/MWh]		$LCOE$ [€/MWh]
Scenario	Season			$d_{om} = 0.01$	Kaplan Type		I_t		$k_a = 11.6536$
A	18/19	min	456 000	4 560	DR	398.44	min	11.44	109.65
							mean	23.64	226.52
		mean	942 000	9 420			max	46.43	444.86
					RR	322.20	min	14.15	135.59
		max	1 850 000	18 500			mean	29.24	280.12
							max	57.42	550.12
	19/20	min	342 000	3 420	DR	203.87	min	16.78	160.73
							mean	34.68	332.26
		mean	707 000	7 070			max	68.08	652.30
					RR	148.86	min	22.97	220.12
		max	1 388 000	13 880			mean	47.49	455.04
							max	93.24	893.36
B	–	min	45 600	456	IV	156.72	min	**2.91**	**27.87**
		mean	94 200	942			mean	**6.01**	**57.59**
		max	185 000	1 850			max	11.80	113.09

Only scenario B seems to be marginally viable for the minimum and mean values of the investment interval, also resulting in a NPV = 101 270 € for the best case.

VII. RESULTS

The estimated annual consumption, E_{req} as well as the annual producible energy E_a are summarized in Table XVIII.

Table XVIII: Annual demand vs annual generation.

E_{req}			E_a		
Original Scenario (°)			Scenario A		
Pumps	E_i^o [MWh]		Season	E_{DR} [MWh]	E_{RR} [MWh]
2	660.17		18/19	398.44	322.20
3	554.36		19/20	203.87	148.86
Constructed Scenario			Scenario B		
Pumps	$\bar{E}_i^v$ [MWh]	$\bar{E}_i^r$ [MWh]	Season	$E(IV)$ [MWh]	
2	625.15	646.83	-	156.72	
3	524.79	542.99	-	-	-

Although scenario B was found to be conservatively viable, one should not assume this is indicative of project viability, since the FDCs are incomplete, the head determined may not be realistic, the energy is being estimated with a simplified model, the investment based in installed capacity values does not account for the difference in cost of building the reservoir, the cost of similar projects in Mozambique is unknown, etc.

VIII. CONCLUSION

It bears mentioning that energy consumption had to be estimated from water requirements, which in themselves were estimated from limited climate data and an incomplete picture of agricultural practices. This being said, with incomplete hydrologic records and a poorly characterized topography, scenario A led to a greater energy production at a naturally higher cost, associated with the construction of the dam. As for scenario B, which is focused in limiting the flow available to the turbine, the producible energy is reduced while also requiring a smaller investment. Ultimately, neither scenario can suppress the dependence on the grid due to technical constraints. It is not possible to ensure the rated power for the necessary time (duration of irrigation cycles) given the low head of the terrain and the decrease in flow characteristic of the dry season. However, with all available information and under the assumptions made, scenario B, provided a reservoir exists, still comprises the only cost-effective solution, with a $LCOE = 57.59$ €/MWh for an estimated medium value of investment $I_t = 94\,200$ €, allowing a partial coverage.

In regard to future recommendations, more complete data on the irrigation system and agricultural practices would yield more accurate results, and access to energy bills would allow the validation of results. Ultimately, irrigation cycles could be adjusted to make a more efficient use of water, and hence energy, by dynamically measuring climate parameters, determining water requirements with a smaller time step, adjusting crop needs by designing a flexible irrigation system, that faced with the state of the river, i.e., value of flow, could determine through a control system what volume of water could or should be stored, how much could be expected from each source (grid or hydro), etc.

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