Exploring Hydropower Options at A Wastewater Treatment Plant - A Case Study

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Abstract—**In the intensified search for more renewable energy generating opportunities, this study looks at the hydropower potential at the discharge point of a wastewater treatment plant. A comparison of the energy yield is drawn between installing the hydropower scheme at the discharge point of the wastewater treatment plant, against implementing it in the river in which the plant is discharging. The resultant energy potential of the two sites is compared to indicate the maximum possible energy yield. The specific site conditions were obtained, and the calculated flow characteristics are used in conjunction with prior literature to determine suitable turbine options. The obtained results show that the hydropower scheme at the wastewater plant generates more power than the scheme at the river. The Archimedes screw turbine was also found to be the best-suited turbine at the outflow of the wastewater treatment plant. The turbine at the plant generates 7.9 kW and 9.8 kW powers for the low and high-efficiency turbines, respectively, while the waterwheel only produces an average of 4.5 kW. This study proves that a hydropower system can be implemented successfully at a wastewater treatment plant with a head of 1.5 m. Conclusively, the potential energy yield found serves to give authorities and prospective owners early indication if there is merit in hydropower projects. If economically viable turbines are designed, hundreds of wastewater treatment plants can be retrofitted to generate many gigawatt-hours per year.**

Keywords— renewable energy, hydropower potential, Archimedes screw turbine, wastewater treatment plant.

I. INTRODUCTION

Since the global warming phenomenon was highlighted, there is a worldwide drive to find alternative renewable energy sources. South Africa is one of the many countries worldwide that are exploring multiple options to supplement its energy generation capacity, to meet the demand of its energy-intensive economy [1]. The country has been going through a strenuous period in terms of energy supply since 2008. It has implemented frequent rolling blackouts or load shedding to reduce the demand and keep the electricity grid from total collapse [1]. Since 2010, the country's electricity supply has declined in contrast with the expected growth of 3% [2]. Although many new renewable energy projects have been commissioned and are still in the pipeline, there is still a big shortfall in electricity supply. The share of renewable energy compared to the total energy basket is also low compared to coal [2]. South Africa has signed the Paris agreement whereby it must reduce its greenhouse gas emissions. These emissions contribute to half of the total harmful emissions of the country [2]. These factors highlight the need to find as many renewable energy projects as possible for the country.

South Africa is currently generating electricity from a host of water treatment plants ranging from a smaller 15 kW pilot system at the Pierre van Ryneveld reservoir in Pretoria to a 1.475 MW hydropower turbine on the Faure water treatment plant in Cape Town [3]. From the above, it can be seen that not much attention is given to the smaller pico-hydropower facilities. Understandably so because of the limited impact it has on the overall needs. However, it was found in prior research that there could be sufficient opportunities in the pico- and micro hydropower category of small hydropower to make a significant contribution in Africa [3], [4]. The focus of this present study is on small hydropower opportunities. Specifically pico-hydropower at the outlet of water treatment facilities. The study investigates a case example of a wastewater treatment plant known as the Zandvliet Wastewater Treatment Works (ZWWTW) in Cape Town. The discharge outflow data is obtained to determine the maximum potential energy that can be generated from the plant's outflow. To simply look at the hydraulic potential of the flowing water can be inaccurate. Moreover, since different turbines have varying efficiencies in the same conditions, the selected turbine influences the final energy yield. Hence the discharge characteristics are used to select the best-suited turbine type to produce the highest possible electric energy, as shown in Fig. 1.

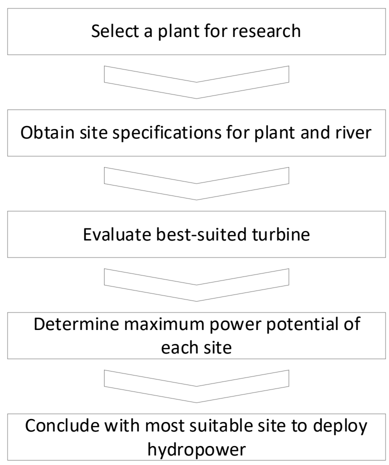

Fig. 1: Process of hydropower research at the wastewater treatment plant.

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II. SITE SELECTION

The Zandvliet Wastewater Treatment Works (ZWWTW) in Cape Town, South Africa, was arbitrarily selected for this research. The ZWWTW plant pumps recycled water into a channel, as shown in Fig. 2. This canal of about 200 m channels the discharged water of the ZWWTW towards the Kuilsriver, where it travels for about seven kilometers to the sea. A comparison is done of the hydropower potential at the point of discharge of the plant, as opposed to the hydropower potential at the river after the connection point of the canal.

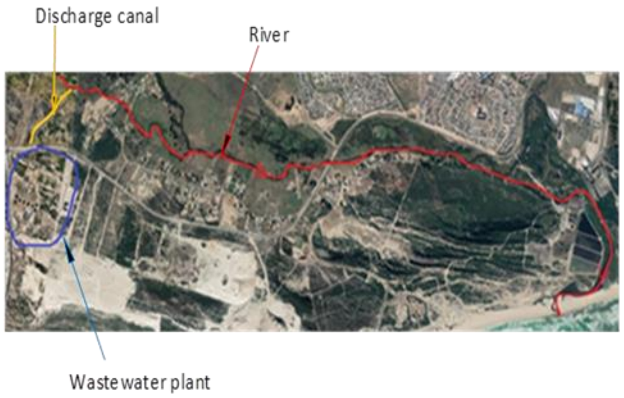

Fig. 2: Geographical position of the wastewater plant Adapted from [5].

A. Plant Site Specifications

The first step of this research is to determine the site specifications on the discharge point of the ZWWTW into a canal and the specifications of the Kuilsriver after the entry point of the joining canal. The specifications include the potential head, volume of water, and flow rate.

Fig. 3 shows the discharge outflow that was obtained from Cape Town municipality. The daily flow over the full year shows an average of 67 million litres per day. This converts to a continuous flow of 767 litres per second.

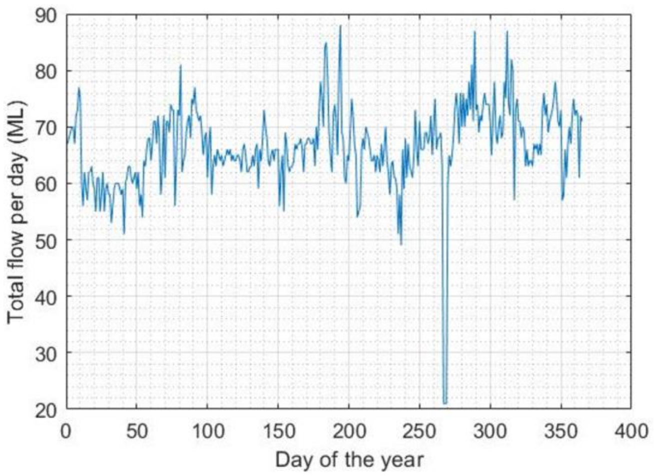

Fig. 3: Total daily flow of ZWWTW over 365 days.

The topographical diagram of the ZWWTW area in Fig. 4 shows the height difference from the plant to the river. The outlet of the plant area is about 15 m above sea level, while the highest point on the river has an altitude of 10 m, which corresponds to a difference of five meters. This converts to a possible head of at least two meters for a potential hydropower scheme. In this research, a safe head of 1.5 m is assumed and established.

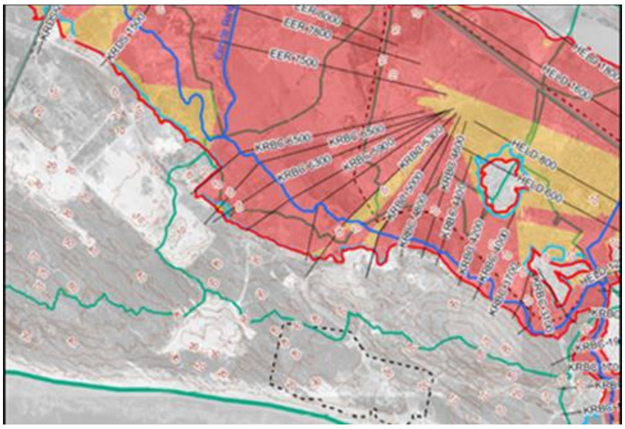

Fig. 4: Topographical map of the wastewater plant area [6].

B. Turbine Selection at the Plant

Fig. 5 shows various turbines that are positioned with their respective head and flow ranges. The figure also shows that the Archimedes screw turbine (AST) and the waterwheel are suitable for the conditions of 1.5 m head and 2.8 m^3/s flow rate at the discharge point [7].

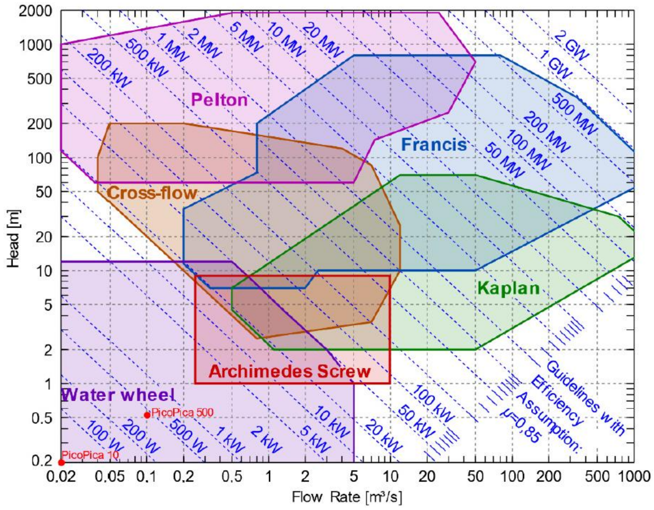

Fig. 5: Turbine chart according to head and flow [7].

Table I presents a list of relevant turbines that were developed for canals and water treatment plants' outfalls [8], [7].

TABLE I: ULTRA-LOW HEAD TURBINE OPTIONS AND THEIR APPLICATIONS

Type	Application
Archimedean screw	Canal, Wastewater treatment plants (WWTP)
Kaplan	(WWTP)
Hydro engine	Run-of-river
Vertical axial hydrokinetic turbine (Vaht)	Canal
Modular waterwheel	Canal

In similar research on hydropower at a wastewater treatment plant, Mumtaz [9] compared only the Kapan and the Archimedean screw turbines. The assessment was done on the criteria of cost, energy generation performance, construction

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duration, efficiency, and fish-friendliness amongst others. The results of this assessment (Table II) show that the AST is superior in most of the categories.

TABLE II: ASSESSMENT RESULTS OF THE KAPLAN AND ARCHIMEDEAN SCREW TURBINES ON VARIOUS CRITERIA (ADAPTED FROM [9])

Criteria		**Turbine**	
		Kalan	**Archimedean screw**
Technical	Energy generation performance (%)	85	93
	Construction duration (months)	10	19
Economic	Investment cost (EUR/kW)	1965	2250
	Payback period (year)	3,18	2,38
Features	Fish-friendly	No	Yes
	Aeration capacity	No	Yes

In other research on hydropower, Niebuhr [10] found that the hydrokinetic turbine is well-suited for application in canals in South Africa. Although the Kaplan and hydrokinetic turbines are seen as good candidates for wastewater treatment plants, these turbines are not well suited for applications where the head is below 2 m [11], [9]. The prominent turbine manufacturers do not grade these turbines accurately at a head of 1.5 m. The AST on the other hand is shown to have good efficiency at a head of 1.5 m. In similar studies of hydropower generation at a wastewater treatment plant, the AST was found to be the most suitable turbine [9], [12].

Another feature of the AST is its ability to allow relatively large objects through without clogging, a feature not found in the other turbines. This fish-friendly feature is a major plus point for this application because debris is often witnessed at outlet points [9]. From the above arguments, the AST (Fig. 6) stands out as the best-suited turbine for this application.

Fig. 6: Archimedes turbine at an industrial plant [7].

C. Plant Turbine Output

There is no perfect design theory for AST [7], and there is no mathematical model that describes the power generation of the AST [13]. Due to the complexity and varying approaches to a yet unfinalized AST design [14], this study aimed to find a suitable method that can be used to produce a functional AST design. The design of the AST is not covered in this study but the basic operation and factors that affect its efficiency are investigated. The AST comprises a fitted screw inside a trough and enclosed in a tube. The complete unit is installed at an incline of between 20° and 35° to allow the flowing liquid to pass through it, due to gravity. The screw blades vary in number as well as the angle at which the blades are fixed to the main shaft. Water flows along the bottom of the screw trough and lies in the individual compartments of the blades, called buckets. The potential energy of the water exerts pressure on the blades, causing the screw to turn and produce mechanical energy. The shaft is coupled via a gearbox to a generator, which generates electrical energy. The general formula for hydropower generated by AST is given by [14],

$$P = \eta \, . \, \rho \, . \, g \, . \, H \, . \, Q \, , \qquad (1)$$

where P is the potential power of the hydropower site, η is the efficiency of the turbine, ρ is the density of the liquid in kg/m^3, g is the gravitational acceleration, H is the effective head, and Q is the mass flow rate in m^3/s [14], [15]. The general equation for hydraulic power of a site is given by,

$$P_{hyd} = \rho \, . \, g \, . \, H \, . \, Q \, . \qquad (2)$$

The potential hydraulic power of a site with the Archimedes screw turbine is given by the equation,

$$P_{hyd} = \rho \, . \, g \, . \, H \, . \, Q \, . \, m \, . \, \Delta y \, , \qquad (3)$$

where m is the number of turns of the blades and Δy is the height difference between the blades.

The mechanical power of the screw (P) can also be given by the torque (T) times the angular velocity (ω) of the screw, as given by,

$$P = T \, . \, \omega = 2\,\pi\, n \, / \, 60 \, . \qquad (4)$$

However, the values of torque and velocity are not available in this study, the mechanical power will be derived from (5):

$$P_{mech} = P_{hyd} \; * \, \eta, \qquad (5)$$

Where η is the efficiency of the turbine.

Various studies have been undertaken to determine the optimum specifications for the best efficiency of the AST, as well as do a comparison between the modelling and experimental results of the various approaches. This research selectively uses a combination of these results to model the proposed AST for the highest efficiency. Some of the efficiencies that were found in the previous literature that focus on sizes of AST vary from 72% to 89% [16], [17]. The efficiency values chosen to model the potential output power for this study are 72% (low) and 82% (high), respectively. These values were selected from prior research, to be realistically close to the lowest and highest efficiency of an

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AST. The two values thus represent the range of AST potential power that is modelled.

Fig. 7 shows a schematic diagram of the Archimedes screw turbine components used to determine output power.

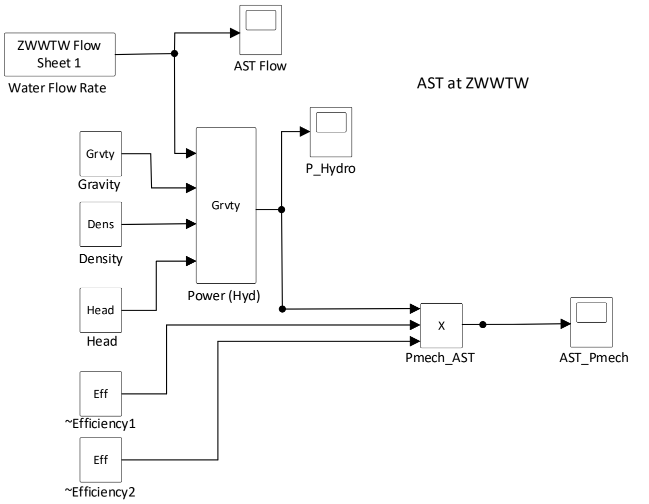

Fig. 7: Simulink diagram of the Archimedes screw turbine components.

III. AT THE RIVER SITE

A. Site Specifications

The point of connection from the linking canal is at the lower course of the Kuilsriver. This area has a low gradient, with slow flow, relative to the middle and upper course of the river. The river flows for another 7 km to the sea from an altitude of 7 m, with an average stream gradient of 1m per kilometer. Fig. 8 shows a typical section of the river.

Fig. 8: A section of the Kuilsriver showing a depth stick.

The total volumetric flow of the Kuilsriver near the discharge point of the ZWWTW was calculated using the float method which is one of the velocity-area methods [18]. In this method, the cross-sectional area of the river is measured. A float is then used to measure the velocity or speed of displacement of the cross-sectional area, over a demarcated distance. The cross-sectional area is then multiplied with the velocity or total displacement to get the volumetric flow in cubic meters per second [19]. This experiment was carried out over the four seasons of the year and is recorded in Table III An average flow of 2.85 m^3/s was obtained.

TABLE III: THE MEASURED SEASONAL FLOW OF THE KUILSRIVER

Month	Width	Height (ave)	Area m²	Velocity m/s	Flow m³/s
Jan	6	0,28	1,68	0,83	1,40
Feb	6	0,20	1,20	1,00	1,20
Mar	6	0,25	1,50	0,90	1,35
Apr	6	0,28	1,68	0,83	1,40
May	6	0,32	1,92	1,15	2,20
Jun	6	0,60	3,60	1,40	5,04
Jul	6	0,70	4,20	1,62	6,80
Aug	6	0,70	4,20	1,57	6,60
Sep	6	0,65	3,90	0,83	3,24
Oct	6	0,40	2,40	1,29	3,10
Nov	6	0,35	2,10	1,19	2,50
Dec	6	0,30	1,80	1,00	1,80
Average	6	0,40	2,40	1,19	2,86

The seasonal flowrate of the Kuilsriver at the discharge point of the ZWWTW is transformed into a monthly flowrate shown in Fig. 9. A clear peak flow of 6800 l/s that is visible in one season, is more than double the rest of the year's flow.

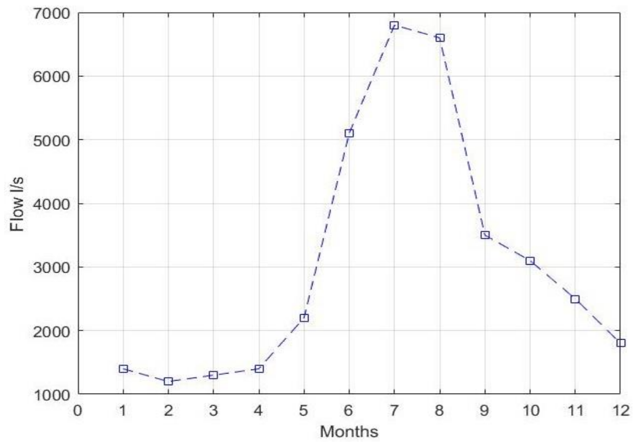

Fig. 9: Monthly flowrate of the Kuilsriver.

If the river flow were to be used in its natural state as recorded in Table 2, the only realistic workable turbine is the undershot waterwheel or stream wheel in Fig. 10 [20].

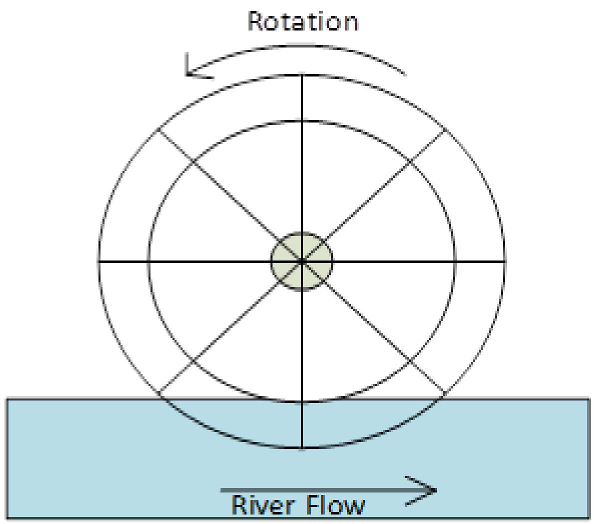

Fig. 10: Undershot waterwheel.

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The Sagebien and Zuppinger waterwheels are the most efficient according to Quaranta and Revelli [21] but according to Denny [22], the Poncelet undershot waterwheel is just 30% efficient. In the present study, the power output of the undershot waterwheel is calculated using the universal hydropower formula in (1).

IV. Results and Discussion

The mechanical power output is calculated using (4) since the screw torque and rotational velocity are unavailability. For the power calculations, losses are negligible and assumed to be the same on both sites. The power output produced by the AST over 365 days using a low and high efficiency of 72% and 82% respectively, as depicted in Fig. 11. The resultant average powers are 6.85 kW and 9.8 kW respectively.

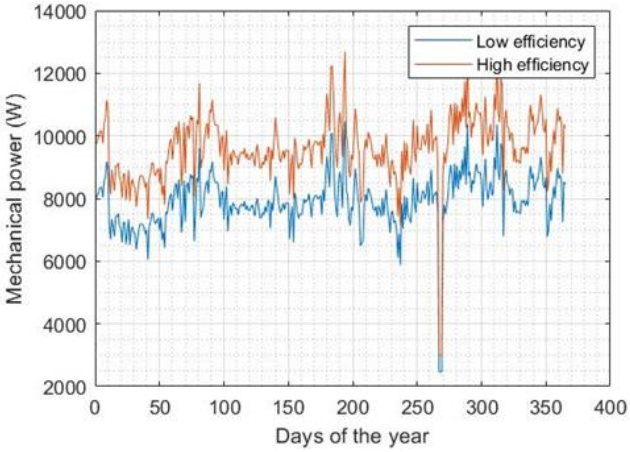

Fig. 11: Daily mechanical power of the AST at the ZWWTW at low and high efficiency.

Fig. 12 shows the hydraulic power in comparison with the river flow rate. The potential hydraulic power is calculated using (2), which is the head, flow, gravity, and density of the water multiplied together. The resultant graph shown in Fig 12 is proportionate to the water flow. Moreover, there is a clear peak around month seven. In month seven, the flow peak at 6800 l/s. This peak flow corresponds to a potential hydraulic power of 46 kW.

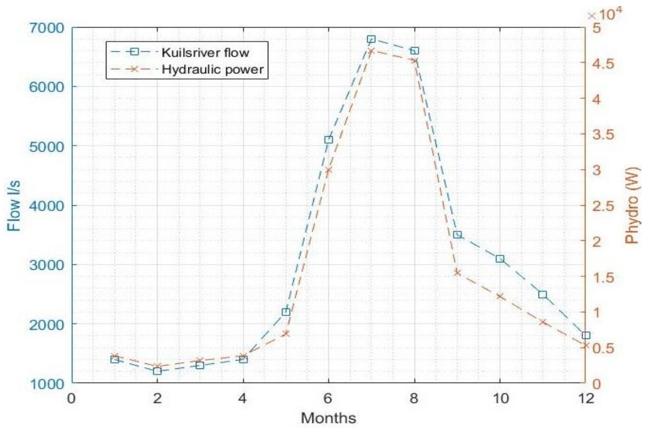

Fig. 12: Relation between the river water flow and the potential hydropower.

The mechanical power of the undershot waterwheel at the Kuilsriver is compared with the potential hydraulic power in Fig. 13. As mentioned in Section III, the mechanical power of the waterwheel is derived from the hydraulic power, by multiplying it with a 30% percent efficiency as in (1). The result shows that the mechanical power output that peaks at 14 kW is much less than the available hydropower that peaks at 46 kW.

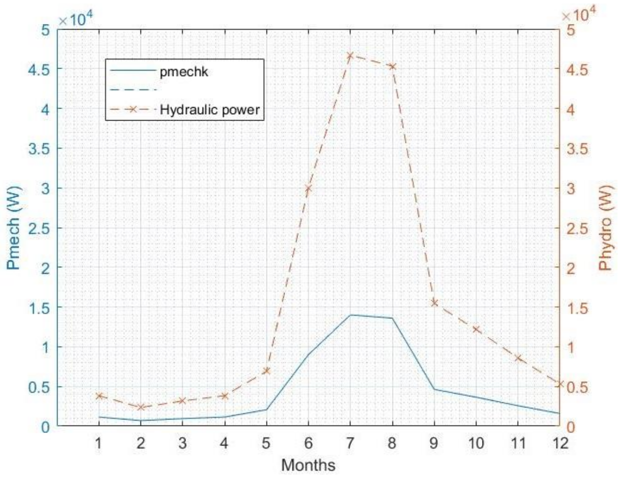

Fig. 13: Kuilsriver monthly water flows with waterwheel output power.

Fig. 14 presents the mechanical power generated by the AST at the ZWWTW plant and the undershot waterwheel at the river. The low and high-efficiency graphs of the AST show that the AST power is flat compared to the power of the waterwheel that is showing a peak in the middle months. The AST produces an average power of 7.9 kW (low efficiency) and 9.6 kW (high efficiency), while the waterwheel generates an average of 4.5 kW, although it has a peak of ten times that size.

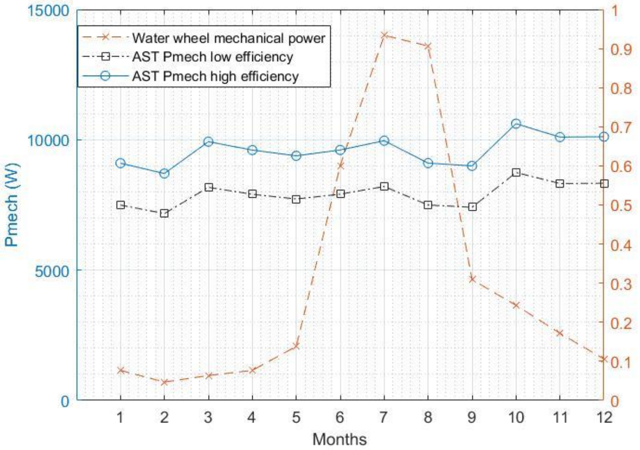

Fig. 14: Relation between the output power at the wastewater treatment plant and the undershot waterwheel at the river.

V. Conclusion

This study investigates the hydropower potential at the outlet of the Zandvliet Wastewater Treatment Works, as well as in the river in which the plant discharges. The study revealed that the Archimedes screw turbine is the best-suited turbine for the plant conditions. The undershot waterwheel was found to be the only usable turbine in the river, if no funnelling of the river flow is carried out. It was further found that the lowest efficiency Archimedes screw turbine that is deployed at the ZWWTW, generates more power than the waterwheel that is installed at the river. However, the selected turbine at the river has a very low efficiency of 30% and more research needs to be done on turbines at river and broad canal sites. Further studies are required on methods to improve water flow over the installed hydropower turbine. This makes

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it more competitive with turbines at the discharge point of industrial plants.

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