A Numerical Study to Analyze the Lateral Distance between Hydrokinetic Turbines in a Canal: A Case Study

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Abstract: Small hydropower has been evolved as a solution to the adverse impact of large hydropower on the environment. In small hydropower, energy can be harnessed by static and kinetic method. Energy is harnessed by creating water head in static method and using flow velocity in kinetic method. Now-a-days hydrokinetic technology is growing extensively and emerging as a promising technique which utilizes the flow velocity for the energy generation. In the present study, an attempt has been made to define the lateral distance between two hydrokinetic turbines with the aim to deploy maximum turbines along the width of the canal. The methodology of the study comprises of five steps involving data collection from the study area, turbine designing, numerical simulation followed by post processing and analysis of the results. The data collection includes bed width, full supply level (FSL), side slope, bed slope, discharge and velocity of the canal. Among various hydrokinetic turbines, Savonius is selected due to its better self-starting behaviour. In the present study, turbine is considered as fully immersed in order to utilize the full water energy for rotation. The determined wetted flow area governs the dimension of the Savonius hydrokinetic turbine. The dimension of the Savonius turbine is calculated using optimum design parameters of Savonius turbine configuration. In the numerical simulation, flow area of the channel act as a stationary domain whereas the turbine enclosure behaves as a rotating domain. The entire domain is numerically simulated for different flow velocities at an optimum TSR (tip speed ratio). The performance of the turbine is analysed through power coefficient. The performance of two turbines when compared with the performance of a single turbine is different because the presence of second turbine affects the performance of first turbine and also have a significant effect on the hydraulic behaviour of the channel. Therefore, the lateral distance between two turbines is decided on the basis of minimum interference of one turbine on another. It is concluded that the lateral distance should always be decided such that the turbine have zero influence on the performance of other turbine. This way will lead to maximum energy extraction with minimum change in the hydraulic behaviour of the canal.

Keyword: Hydrokinetic energy; Blockage ratio; Savonius hydrokinetic turbine; Power coefficient; computational fluid dynamics (CFD)

1. Introduction

The contribution of renewable energy in the global electricity production is 26.2% of which 15.8% is the share of hydropower (REN21, 2019). Hydropower is the largest contributor in renewable energy but have various negative impact on biodiversity and now-a-days, society aims to produce energy in an efficient and sustainable manner. This is the reason that growth rate of large hydropower is reduced. But unlike solar and wind, hydro is 24X7 available, reliable and predictable source of energy and therefore instead of out-looking this source, it is better to utilize the water energy more effectively. Static and kinetic are the two different methods through which water energy can be harnessed (Khan, Iqbal, & Quaicoe, 2008). Static method is a conventional method whereas kinetic method is a newly emerging technique for energy extraction. A comparative study of static and kinetic methods is illustrated in Table 1.

Table 1: Static method vs kinetic method

Parameter	**Static Method**	**Kinetic Method**
Energy utilized	Potential head	Kinetic head
Theoretical equation of power	$P = \rho gQH$	$P = \frac{1}{2} \rho A V^3$
Principle	Utilize hydraulic head	Utilize flow velocity
Device	Conventional turbines	Wind turbines
Diversion structure	Weir/Barrage/Dam	No diversion structure
Application	Rivers and canals	Oceans, tides, rivers and canals
Utility	• Hydropower generation	• Irrigation for agriculture, Milling of food grains, • supply of fresh water, • Hydropower generation
Impact on biodiversity	• Alter the ground water level • Dry the downstream river stretch • Rehabilitation & resettlement of people • Land submergence • Diversion of natural pathway • Noise pollution	• Minimal civil construction • Do not divert the natural river path • Turbines works at lesser rpm and thus less noise pollution • No impact to biodiversity

Hydrokinetic technique is one of the most promising technology of renewable energy which have minimum environmental impact and high potential in ocean, canals and rivers. Hydrokinetic technology is a zero-head technique in which kinetic energy of water is utilized for energy generation instead of potential head (Khan et al., 2008). Hydrokinetic technology is also known as in-stream scheme of small hydropower (SHP). The principle of hydrokinetic turbine is similar to wind turbine (NAKAJIMA, IIO, & IKEDA, 2008), only the fluid is replaced by water and the domain is restricted to flow area. Hydrokinetic devices are also known as instream, zero head, water current and freestream turbine. Hydrokinetic turbine is categorized into axial and crossflow turbines. Axial flow turbines are preferred in marine and oceanic climate and have their rotor parallel to the flow direction whereas crossflow turbines are preferred in rivers, canals and have their rotor orthogonal to the flow direction (Kumar & Saini, 2016). The flow depth is limited in river, canal and therefore, require such a turbine which have larger diameter with shorter height unlike axial flow turbines (Khan, Bhuyan, Iqbal, & Quaicoe, 2009).

The installation and operation of turbine will have an impact on the flow condition of the channel (Sood & Singal, 2019). The impact will be in terms of reduced velocity downstream of turbine, increased velocity along the width due to channel blockage and wake recovery distance along the length. This reduction and recovery of flow velocity will change the hydraulic behaviour of canal. This reduced velocity will affect the performance of second turbine, if installed either just downstream of first turbine along the length or across the width. The location of second turbine should be selected such that the influence of one turbine is zero on the performance of other turbine. No such study is available to determine the installation distance between two turbines in the canal. Therefore, three dimensional computational fluid dynamics (CFD) simulations have been carried out under the present study in order to analyse the impact of turbine operation on flow condition for a selected site. In order to analyse the impact, following objectives have been addressed:

i. To determine the impact on flow condition of turbine operation.
ii. To determine the location of second turbine along width at such a distance that it has zero impact on the performance of first turbine.
iii. To select the optimum turbine diameter which have maximum energy generation.

2. Methodology

The complete study comprises of five steps involving data collection of the study area, turbine designing, numerical simulation followed by post processing and analysis of the results as shown in Figure 1. The first step is the collection of data which includes bed width, full supply level, side slope, bed slope, discharge and flow velocity of the study area. The second step is to carry out the literature review for the selection of suitable rotor among various crossflow hydrokinetic turbines. The third step is the turbine dimensioning along with the selection of its optimum parameters. Using ANSYS 15.0 software, numerical simulation of the selected turbine along with channel domain is the fourth step. The fifth step is the post processing of the numerical simulation in the CFD-post module of ANSYS 15.0 which deals with interpretation of the results by analyzing the velocity and performance parameters of the study.

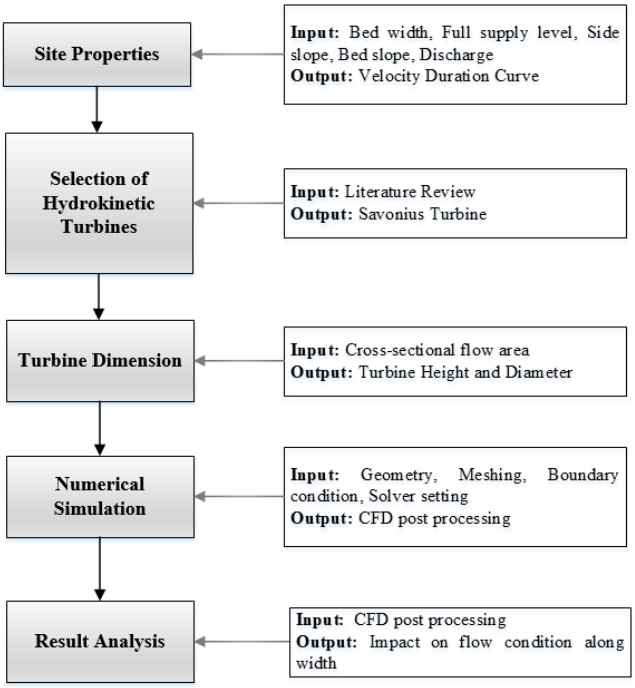

Fig. 1 Methodology

Study Area

The study area is a lined canal and the selected location is 30 meter upstream of Sonali Aqueduct of Parallel Upper Ganga Canal (PUGC) near Roorkee town in Haridwar district of Uttarakhand state of India. The canal is trapezoidal in shape having 24 m bed width, 0.25/km bed slope and 2H:1V side slope with brick lining. Discharge, flow depth, bed slope and channel cross-section data of three years i.e. 2015, 2016, 2017 is used for determining the flow velocity. Two different flow velocities were determined considering two manning's coefficient i.e. n as 0.017 and 0.018. Similarly, flow velocity is determined for all the discharges and plotted in Figure 2 as velocity duration curve. The figure 2 shows that velocity varies from 0.84 to 2.14 m/s. Therefore, the range of flow velocity used in the study is 1.0, 1.5, 2.0 and 2.5 m/s.

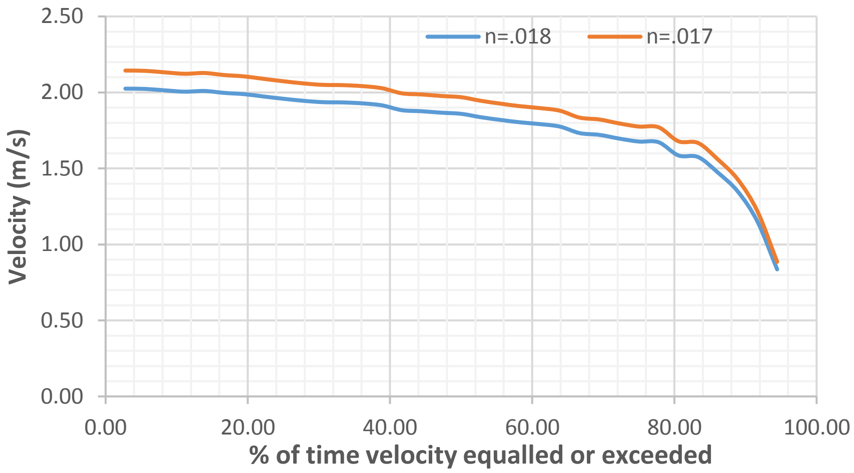

Fig. 2 Velocity duration curve of PUGC RD 30 m upstream of Solani aqueduct

Selection of Hydrokinetic Rotor

Hydrokinetic rotor extracts energy through hydrodynamic forces acting on the rotor blades. Drag and lift are the two types of hydrodynamic forces. On this basis, cross flow turbines are categorised as drag based and lift based configurations. Savonius rotor is the most common example of drag based configuration (Wilson & Lissaman, 1974) and Darrieus rotor is the example of lift based configuration. Driving force, efficiency, fluctuation in torque and self-starting behaviour are the various parameters on which these rotors can be distinguished. The efficiency of Savonius rotor is low as compared to Darrieus turbine. Although, the efficiency of Darrieus rotor is remarkable but have self-starting problem. On contrast, Savonius rotor is functional even at low fluid velocity. Therefore, in the present study Savonius hydrokinetic rotor is selected. In 1920, Sigurf J. Savonius, a finish engineer invented Savonius turbine which consists of two semi-circular cylinders. One of the blade is known as advancing blade and the other is known as returning blade (Roy & Saha, 2013). Drag force difference is responsible for the rotation of rotor blade. The other advantages of Savonius hydrokinetic turbine are low cost, simple in design, capable to self-start, low vibrations and low fluctuation in torque (Kumar & Saini, 2016).

Design Parameters of Savonius Hydrokinetic Turbine

Aspect ratio, overlap ratio, end plates, number of blades, tip speed ratio are the design parameters of Savonius hydrokinetic rotor (Kumar & Saini, 2016). The optimum value adopted in the study is provided in Table 2. Table 2 also highlights the importance of these parameters on the turbine's operation.

Table 2: Optimum values of design parameters of Savonius rotor

Parameters	Expression	Impact on Performance	Optimum Range
Aspect ratio (Damak, Driss, & Abid, 2013; Saha, Thotla, & Maity, 2008)	$AR = \frac{H}{D}$	Enhancement in the torque generation as diameter increases but decreases the angular speed of rotor.	1.58
Overlap Ratio (Zeid, Abid, Sarhan, & D, 2012)	$G = \frac{e}{D}$	Reduction in torque generation as overlap ratio increases due to the format of vortex.	0
End plates (Akwa, Vielmo, & Petry, 2012; Hill, Musa, Chamorro, Ellis, & Guala, 2014; Mahmoud, El-Haroun, Wahba, & Nasef, 2012; Menet, 2004; Roy & Saha, 2014)	$D_0 = 1.1 \times D$	Prevents fluid leakage from top and bottom which ensures the pressure difference and improve efficiency.	$D_0 = 1.1 \times D$
Number of blades (Mahmoud et al., 2012; Sheldahl, Feltz, & Blackwell, 1978)	-	Increase in number of blades reduces the efficiency because of the generation of negative rotation.	Two bladed Rotor
Tip Speed Ratio (Pham, 2014; Sheldahl et al., 1978)	$TSR = \frac{\omega R}{V}$	Power coefficient increases with TSR but starts reducing after a certain TSR due to turbulence development.	0.8

Numerical Simulation

The numerical analysis consists of geometry modelling, mesh generation, solver setting (adaption of suitable turbulence model, boundary condition and angular velocity) and post processing of the obtained result. The entire process of the numerical study is shown in Figure. 3.

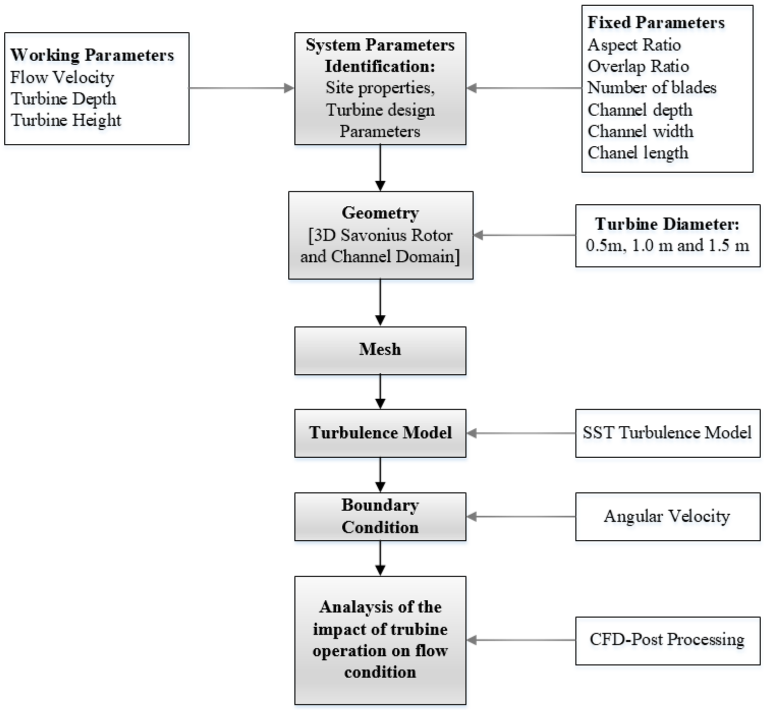

Fig. 3 Numerical simulation process

Geometry

Three dimensional Savonius hydrokinetic turbine and the channel domain is modelled in the geometry module of workbench ANSYS 15.0. Stationary and rotating are the two subdomains of the channel domain. Rotating sub-domain consists of a cylindrical enclosure which is modelled around the Savonius hydrokinetic turbine. This rotating subdomain is assigned with a specified angular velocity as provided in Table 3 and the rotational axis of Savonius hydrokinetic turbine is Y-axis. In order to maintain the flow continuity between stationary and rotating subdomain, two interfaces are modelled around the enclosure circumference namely; channel interface and enclosure interface.

Table 3: Angular velocity of different rotors for different velocity

Velocity (m/s)	**Turbine dia. (m)**		
	0.5	**1.0**	**1.5**
1	3.20	1.60	1.07
1.5	4.80	2.40	1.60
2	6.40	3.20	2.13
2.5	8.00	4.00	2.67

Grid formation

Mesh module of ANSYS 15.0 workbench creates the grid for the complete domain. In the present study, unstructured tetrahedral elements are used. Finer mesh elements are formed in the rotating subdomain of geometry. The mesh quality is determined by skewness, aspect ratio and orthogonal quality. The details regarding these parameters are provided in Table 4 for all the turbines. Further, inflation layer is used for the better quality of mesh near the blades of turbines.

Table 4: Mesh quality parameters

Mesh value parameters	**Turbine dia. (m)**		
	0.5	**1.0**	**1.5**
Number of elements	24795671	32300175	47916821
Skewness			
Maximum	0.870	0.890	0.877
Average	0.215	0.211	0.211
Orthogonal quality			
Maximum	0.998	0.9987	0.999
Average	0.782	0.78639	0.786
Aspect ratio	217	209.260	225

Solver Settings

The range of flow velocity is considered according to velocity duration curve. Shear stress transport turbulence model is used to handle the turbulence and eddies caused due to turbine rotation and flow separation. One revolution is completed in twenty-four time steps. It means that each time step rotates the hydrokinetic turbine by 15-degree. The study has been carried out with 120 time steps i.e. 5 revolutions of Savonius hydrokinetic turbine. The difference in the power coefficient and impact on flow condition caused by 4th revolution and 5th revolution is found insignificant. The time step considered for different turbines and for different velocities is shown in Table 5.

Table 5: Time step size of different rotors for different velocity

Velocity (m/s)	**Turbine dia. (m)**		
	0.5	**1.0**	**1.5**
1	0.081	0.163	0.245
1.5	0.054	0.109	0.163
2	0.040	0.081	0.122
2.5	0.032	0.065	0.098

4. Result Analysis and Discussion

From Figure 2, A large decrease in the velocity is observed through velocity duration curve beyond 83.33 % of time velocity equalled or exceeded. The depth corresponding to this velocity is 2.99 m. therefore, the dimensions of turbine is selected on the basis of available depth. In the present study, three turbines of different diameters are analysed for the selected range of velocity. The rotor depth is determined using the aspect ratio of the Savonius turbine. The determined rotor depth is 0.79 m corresponding to 0.5 m diameter, 1.58 m corresponding to 1.0 m diameter and 2.37 m corresponding to 1.5 m diameter.

Rotor performance with varying diameter

Power coefficient is a dimensionless parameter which expresses the efficiency of the device. The power coefficient obtained in the present study is given in Table 6. The power coefficient obtained varies from 0.179 to 0.198. The validation has been carried out by the earlier published results. Nakajima et al. (NAKAJIMA et al., 2008) performed an experimental work on horizontal aligned Savonius rotor having overlap ratio and aspect ratio as 0.36 and 1.48. The testing was performed at 0.8 m/s flow velocity and reported that maximum power coefficient obtained was 0.2 corresponding to 0.8 TSR. Further, it is stated by Yang and Shu (Yang & Shu, 2012) and Kolekar and Banerjee (Kolekar & Banerjee, 2015) that the power coefficient of the Savonius hydrokinetic turbine increases with increase in flow velocity.

Table 6: Power coefficient for different rotor at different velocities

Velocity (m/s)	Turbine dia. (m)		
	0.5	**1.0**	**1.5**
1	0.179	0.183	0.190
1.5	0.182	0.186	0.192
2	0.185	0.187	0.195
2.5	0.189	0.194	0.198

Theoretical hydrokinetic energy is expressed by equation (1)

$$P_{Theoretical} = \frac{1}{2}\,\rho\,A\,V^3 \qquad (1)$$

Where, P is the hydrokinetic potential in Watt; ρ is density of water in kg/m3; A is the rotor area in m2 and V is the flow velocity in m/s. The available hydrokinetic power is calculated using equation (1) for all three turbines at four different velocities. Further, the obtained power coefficient is used for determining the technical hydrokinetic energy for three turbines under different velocities. Figure 4, 5 and 6 show the available theoretical power and extracted technical hydrokinetic power using a single unit of different dimensions.

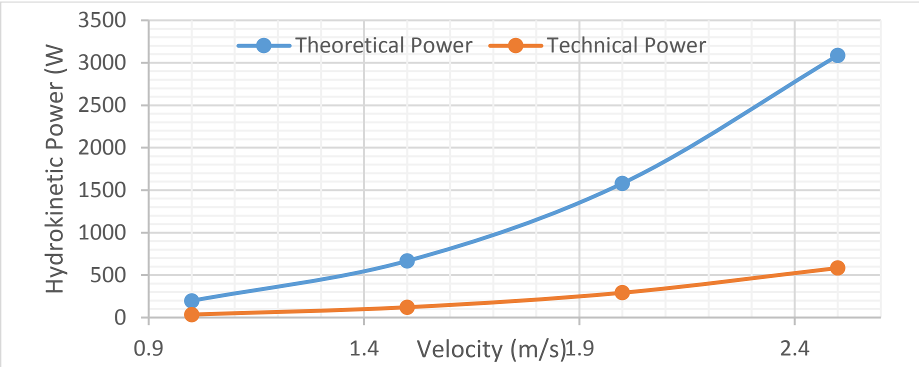

Fig. 4 Theoretical and technical hydrokinetic potential of 0.5 m rotor diameter

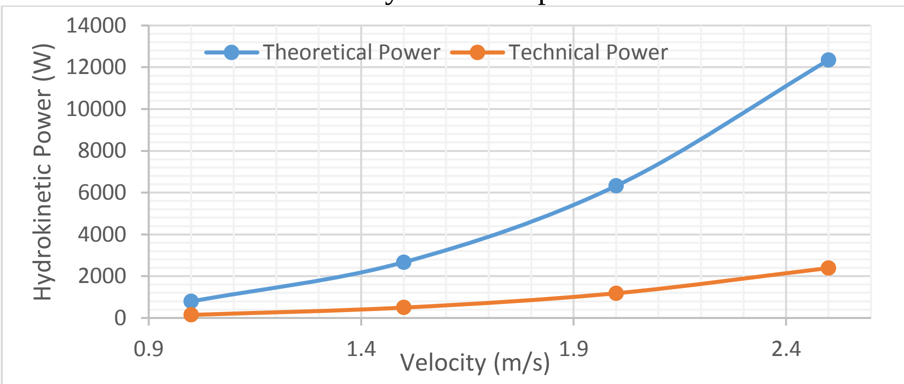

Fig. 5 Theoretical and technical hydrokinetic potential of 1.0 m rotor diameter

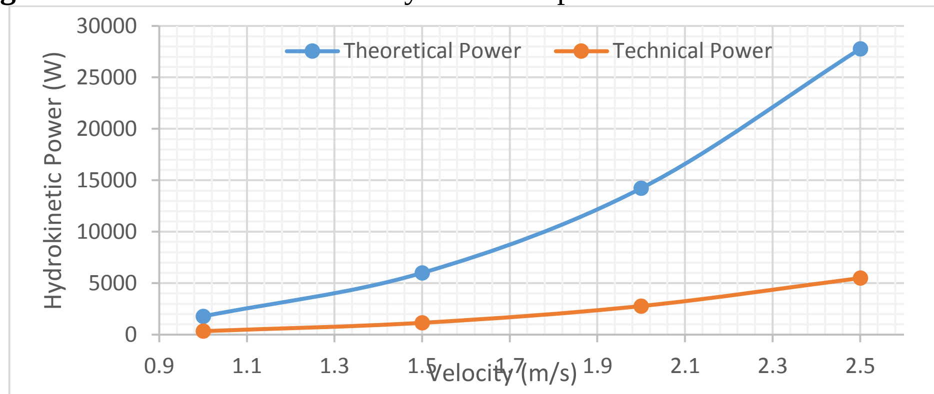

Fig. 6 Theoretical and technical hydrokinetic potential of 1.5 m rotor diameter

Change in flow velocity along the width

During turbine operation, the flow velocity varies along the width of the canal. Turbine operation will change the hydraulic behaviour of the canal by altering the flow velocity along the width as well as along the length. The study shows that the disturbance in flow velocity is limited to a certain distance and will not affect the flow velocity along the entire width of canal. The distance along the width at which the flow velocity reaches its initial velocity will decide the location of second turbine. Turbines with different diameters are analysed for four different velocities i.e. 1.0, 1.5, 2.0, 2.5 m/s. Figure 7 is the graphical representation of the distance at which flow velocity attains its initial value along the width of the canal. The distance for different turbine diameters at which the flow velocity achieves its initial velocity along the length of the canal is shown in Table 7.

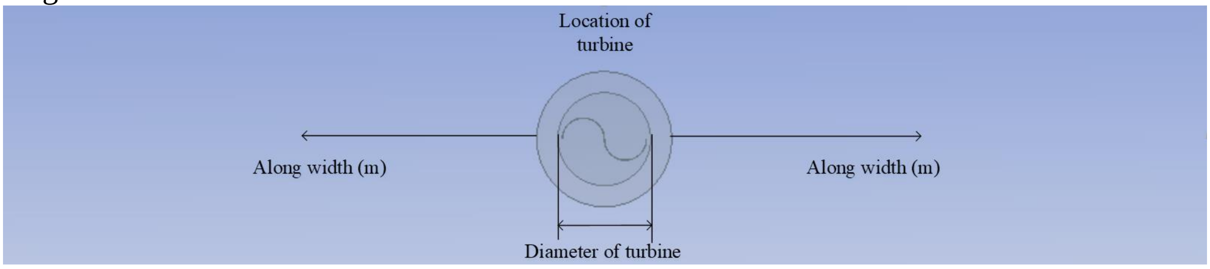

Fig. 7 Graphical representation of the distance at which flow velocity attains its initial value along the length of the canal

Table 7: Distance at which flow disturbances reduce and reache its initial flow velocity along the width of canal

Velocity (m/s)	Left side along width ⟵	Turbine dimension (Channel centre)	Right side Along width ⟶
1.0	0.584	0.5	2.509
	1.293	1.0	6.730
	2.160	1.5	10.022
1.5	0.584	0.5	2.566
	1.288	1.0	6.730
	2.197	1.5	10.047
2.0	0.583	0.5	2.520
	1.285	1.0	6.740
	2.175	1.5	10.058
2.5	0.556	0.5	2.544
	1.280	1.0	6.750
	2.142	1.5	10.097

Selection of optimum number of units for the canal

The optimum turbine refers to the rotor which produces maximum energy throughout the year. The utilization of any of these three rotor depends on the availability of water depth. The depth of rotor are 0.79m, 1.58 m and 2.37 m respectively. The availability of 0.79 m depth is 100%, 1.58 m depth is 91.67 % and 2.37 m depth is 86.11 %. It can be seen that the efficiency of turbine varies from 0.179 to 0.198 for different velocities and different dimensions. Therefore, in the present study, 0.18 is considered as an ideal efficiency of the Savonius rotor for the calculation of hydrokinetic potential throughout the year. Based on the depth, potential is determined for a single unit and given in Table 8.

Table 8: Potential assessment throughout the year with a single rotor having different diameters

S. No.	% Time Equalled or Exceeded	Turbine dia. (m)					
		0.5		1.0		1.5	
		Theoretical Power (W)	Technical Power (W)	Theoretical Power (W)	Technical Power (W)	Theoretical Power (W)	Technical Power (W)
1	2.78	1946.1	350.3	7784.3	1401.2	17514.8	3152.7
2	5.56	1941.0	349.4	7764.1	1397.5	17469.1	3144.4
3	8.33	1914.0	344.5	7656.0	1378.1	17226.0	3100.7
4	11.11	1889.2	340.1	7556.7	1360.2	17002.6	3060.5
5	13.89	1902.5	342.5	7610.0	1369.8	17122.5	3082.1
6	16.67	1867.4	336.1	7469.5	1344.5	16806.4	3025.1
7	19.44	1844.2	332.0	7376.8	1327.8	16597.8	2987.6
8	22.22	1801.2	324.2	7204.8	1296.9	16210.8	2918.0
9	25.00	1760.9	317.0	7043.5	1267.8	15847.9	2852.6
10	27.78	1725.2	310.5	6900.9	1242.2	15526.9	2794.8
11	30.56	1701.1	306.2	6804.4	1224.8	15309.8	2755.8
12	33.33	1696.6	305.4	6786.2	1221.5	15269.0	2748.4
13	36.11	1680.4	302.5	6721.6	1209.9	15123.6	2722.2
14	38.89	1646.1	296.3	6584.5	1185.2	14815.1	2666.7
15	41.67	1566.0	281.9	6263.9	1127.5	14093.8	2536.9
16	44.44	1548.6	278.8	6194.6	1115.0	13937.8	2508.8
17	47.22	1525.1	274.5	6100.4	1098.1	13725.9	2470.7
18	50.00	1506.7	271.2	6026.9	1084.8	13560.5	2440.9
19	52.78	1453.0	261.5	5811.9	1046.1	13076.7	2353.8
20	55.56	1411.1	254.0	5644.6	1016.0	12700.3	2286.0
21	58.33	1374.6	247.4	5498.4	989.7	12371.3	2226.8
22	61.11	1347.8	242.6	5391.1	970.4	12130.0	2183.4
23	63.89	1311.8	236.1	5247.1	944.5	11806.0	2125.1
24	66.67	1219.0	219.4	4876.0	877.7	10971.0	1974.8
25	69.44	1194.6	215.0	4778.4	860.1	10751.3	1935.2
26	72.22	1144.3	206.0	4577.4	823.9	10299.1	1853.8
27	75.00	1105.3	199.0	4421.2	795.8	9947.8	1790.6
28	77.78	1096.5	197.4	4385.8	789.4	9868.1	1776.3
29	80.56	934.6	168.2	3738.2	672.9	8411.0	1514.0
30	83.33	915.6	164.8	3662.3	659.2	8240.2	1483.2
31	86.11	748.6	134.7	2994.3	539.0	6737.3	0.0
32	88.89	575.9	103.7	2303.7	414.7	5183.3	0.0
33	91.67	357.4	64.3	1429.8	0.0	3217.0	0.0
34	94.44	137.0	24.7	547.8	0.0	1232.6	0.0

S. No.	% Time Equalled or Exceeded	Turbine dia. (m)					
		0.5		1.0		1.5	
		Theoretical Power (W)	Technical Power (W)	Theoretical Power (W)	Technical Power (W)	Theoretical Power (W)	Technical Power (W)
35	97.22	0.0	0.0	0.0	0.0	0.0	0.0
36	100.00	0.0	0.0	0.0	0.0	0.0	0.0
Total Technical Power (kW)			**8602.1**		**34052.3**		**74472.0**

Figure 8 shows the graphical representation for determining the distance between the units. The distance is the summation of turbine diameter and the distance up to which the flow is disturbed on both the sides of the unit. After determining the distance between the two turbines, the number of units which can be installed is determined as per the canal width.

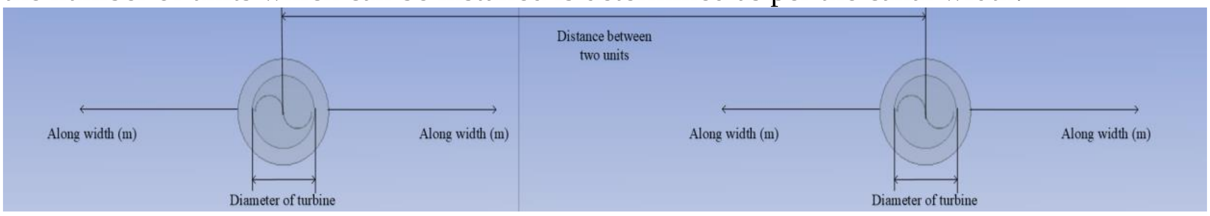

Fig. 8 Graphical representation for determining the distances between the units

- In case of 0.5 diameter of turbine, it is necessary to provide 3.1 m distance between the turbines. It means that seven numbers turbines with 0.5 m dia. can be installed in the canal along the width.
- In case of 1.0 m turbine diameter, 9.1 m distance should be provided between the turbines. Thus, three number of turbines can be installed along the width of canal.
- In case of 1.5 m turbine diameter, 13.7 m distance must be provided between two turbines and only single unit can be installed along the width of canal.

The detail regarding maximum potential which can be harnessed by these turbines is given in Table 9. Table 9 suggest that maximum potential of 102 kW can be harnessed from the canal using three units of turbine having 1 m diameter.

Table 9: Maximum potential with number of units

Turbine dia. (m)					
0.5		1.0		1.5	
Potential from single unit (kW)	Potential from seven units (7 X 8.602) kW	Potential from single unit (kW)	Potential from three units (3 X 34.052) kW	Potential from a single unit (kW)	Potential from a single unit (1 X 74.471) kW

8.602	**60.214**	34.052	**102.156**	74.471	**74.471**

5. Conclusions

In the present study, three rotors of 0.5, 1.0 and 1.5 m diameter are analysed at 1.0, 1.5, 2.0 and 2.5 m/s flow velocities using CFD techniques for a lined canal. Following conclusions have been extracted from the analysis:

- The power coefficient of a Savonius turbine varies from 0.179 to 0.198 with increase in rotor diameter and flow velocity.
- The suggested distance is 3.1 m between two units of 0.5 m diameter, 9.1 m between two units of 1.0 m diameter and 13.7 m between two units of 1.5 m diameter.
- Seven units of 0.5 m diameter, three units of 1.0 m diameter and two units of 1.5 diameter can be installed for the selected study area along the width of canal.
- The array of 0.5 m diameter units produces 60 kW of power, the array of 1.0 m diameter units produces 102 kW of power and the array of 1.5 m diameter units produces 74 kW of power when installed along the width of canal. Thus, rotor having 1.0 m diameter is selected as an optimum turbine with three units.

The determination of number of units along the length is recommended for the future study.

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