Proceedings of the Pakistan Academy of Sciences: A Physical and Computational Sciences 61(4): 381-390 (2024)

ISSN (Print): 2518-4245; ISSN (Online): 2518-4253
http://doi.org/10.53560/PPASA(61-4)673

Pakistan Academy of Sciences

Research Article

Geostatistical Model Development and Assessment of Tidal Stream Energy Resources: A Case Study of Indus Delta, Pakistan

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Abstract: In this paper, an approach is applied by using the Geographical Information System for the development of geostatistical models to assess available tidal stream energy resources of the Indus Delta Creek system. The mean spring tidal current of twelve different locations in the Indus Delta Creek system (Pakistan) is utilized to develop geostatistical models for the prediction of tidal currents at different locations where no data was available. Models are validated and an investigation of prediction error is carried out to select the best model. For the prediction of tidal stream data, various models are collated namely (i) Circular (ii) K-Bessel (iii) Stable, and (iv) Exponential. These models show the range of mean spring ebb current between 1.9 m/s and 2.12 m/s and the range of mean spring flood current between 1.4 m/s and 1.65 m/s. The stable model for mean spring flood current and circular model for mean spring ebb current agreed with the observed ones. Furthermore, the tidal kinetic power density model and bathymetry model are also developed for the selection of potential sites within the study area. Based on results achieved from geostatistical and bathymetry models; deployment of the suitable turbine at the study area is proposed and generation of 2754.7 MW electric power is estimated.

Keywords: Tidal Energy Resources, Tidal Current Turbines, Tidal Stream Energy, Power Density, Tidal Current Meter, Indus Delta, Karachi Coast.

1. INTRODUCTION

The economy of Pakistan has been shrinking since the start of the COVID-19 pandemic in 2019 and the impact of this crisis has seriously distressed the life of common people. Moreover, high inflation, fewer exports, high international market prices, and the worst energy crises have also encumbered the economy. These days, Pakistan is encountering extreme energy crises and the energy demand and supply gap is growing continuously [1]. Additionally, the rising energy demand has increased its cost and the situation has become worse after "the Russia-Ukraine conflict which has so far driven the prices for energy and fuel even higher and caused the price of oil to jump to a high level in almost 14 years, while wholesale gas prices have more than doubled" [2]. During 2020, peak electricity demand reached 25 GW besides 22 GW of electricity production [3] and this shortfall of electricity in the country has not only caused a worse situation in the agricultural industry but has also shut down many industrial plants [4]. Consequently, an increase in the unit price of electricity occurred. The Government of Pakistan is developing policies to reduce fossil fuel dependency by adopting Renewable Energy (RE) sources [5]. Presently, wind and solar energy farms have been deployed in the country [6] but besides having a nearly 1000 km long coastline, the Tidal Stream Energy (TSE) exploration has been neglected so far. TSE is a clean, most predictable, low visual impact, and easily available solution for the existing energy scenario in Pakistan. The Indus Delta region of Pakistan consists of an intricate network of creeks that could be exploited for the deployment of Marine Current Turbines (MCT). However, so far, the Indus Delta creek system has been neglected for the exploration

Received: December 2023; Revised: November 2024; Accepted: December 2024
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of TSE resources. Therefore, a comprehensive study is required to assess the potential of TSE resources. Marine Current Turbines (MCTs) are intended for installation in natural streams, tidal estuaries, and other flowing water facilities; optimized for a specific velocity [7-9]. To increase power production from MCTs, a multiunit array arrangement can be deployed like wind turbine farms [9-11]. Many scholars have worked on array arrangements for TSE extraction [12-15]. The array arrangement using MCT depends on the number of MCTs, dimension of MCT, efficiency of MCT, and the Tidal Kinetic Power Density (TKPD) within the Area of Interest (AOI). The Kinetic Energy (KE) of a tidal stream is calculated by [16]

$$KE = (1/2)\ \rho A V^3 \qquad (1)$$

Where ρ is the density of seawater kg/m^3, A is the cross-sectional area in m, and V is the magnitude of the velocity of seawater in m/s. TKPD is then derived from [17, 18]:

$$P_{KE} = 0.212\ \rho V^3 \qquad (2)$$

It represents the average KE per unit area of MCT aperture. Whereas, more practically, all of this power cannot be harnessed because of Betz's law and the mechanical losses in MCT [17]. Hence, the effective TKPD that MCT can extract is [16]:

$$P_{e.ke} = 0.212\ C_p\ \rho V^3 \qquad (3)$$

Here C_p is the power coefficient and limits the MCT's efficiency. The requirements for the assessment of TSE resources with multiunit array arrangement have been narrated by the researchers [12-15, 19]:

- Selection of suitable sites for MCT depending on water current and suitable depth
- Identification of appropriate type of MCT and its dimensions
- Opting best MCT arrangement for the region
- Investigation of the effect of MCT on the tidal downstream

Aforesaid in view, this study aims to investigate and estimate the TSE resources of the creek region of the Indus Delta, which are so far unexploited and neglected. To assess TSE resources for the study area, tidal stream data was acquired and evaluated for the first time. Since the Area of Interest (AOI) is comprised of a large area and due to the limitation of available tidal data, an approach using a geostatistical model is applied to predict the tidal data at unobserved locations. Moreover, the TKPD model is developed for the first time for the entire Indus Delta region.

2. STUDY AREA AND METHODOLOGY

Figure 1 [20] represents the methodology of the research study carried out for the assessment of TSE resources in the creek region of the Indus Delta, Pakistan. Indus Delta region is found to

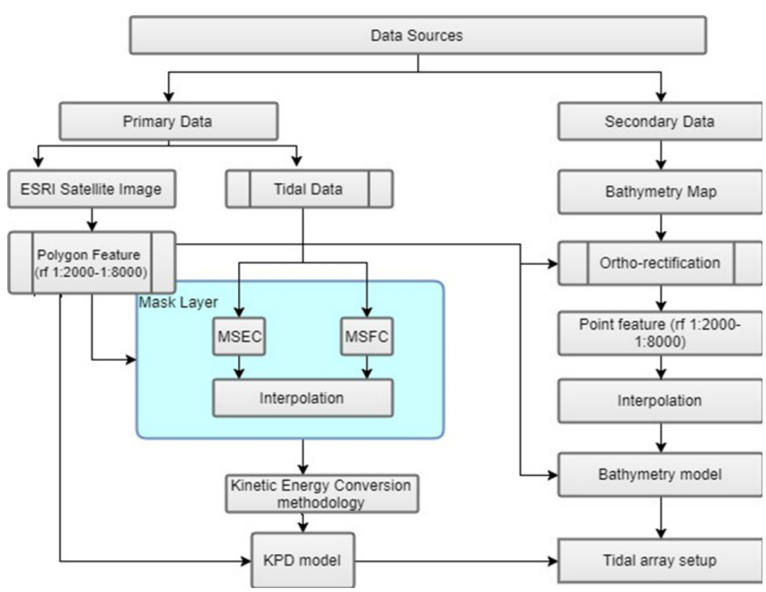

Fig. 1. Methodological framework.

be the most potential site for TSE resources in Pakistan which is around 190 km long, including 17 primary and a large number of secondary creeks extending from Korangi Creek near Karachi to Sir Creek near the Pakistan-India border with an area of 30,000 km^2 [21, 22] as shown in Figure 2. For the development of the TKPD model, 12 sites are considered (see Figure 3) and assigned station IDs. Tidal observations were available only for these sites; therefore these are selected for the TKPD model.

This methodology consists of the acquisition and processing of data, different techniques for assessment of models, model selection, tidal data estimation at an unobserved location, TKPD model development, turbine selection, and power generation from selected turbines. Tidal stream data was acquired from the Hydrography Department, Pakistan, using a Tidal Current Meter (TCM). Tidal data includes the Mean Spring Ebb Current (MSEC) and Mean Spring Flood Current (MSFC) of 12 sites for the duration of 9 years (2005 to 2014) as shown in Table 1. Satellite and bathymetry data acquisition and processing were carried out as mentioned by Insaf *et al.* [23].

For the GIS model setup; the AOI Land digitization layer, tidal stream data, and socioeconomic layer were transported to the geodatabase for processing in the GIS environment. The prediction model of TS data was created by using ArcGIS (v.10.2) and Geostatistical Analyst extension. Geostatistical techniques can interpolate

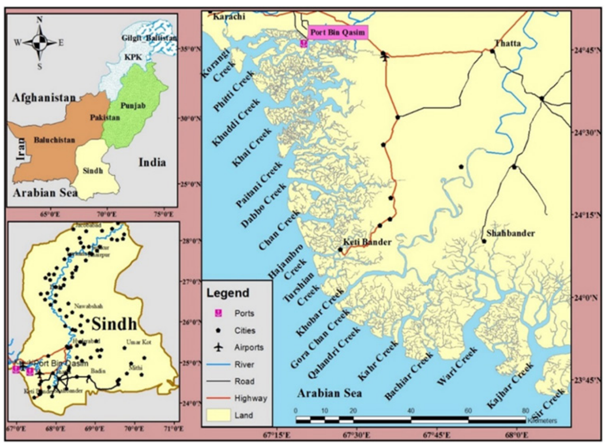

Fig. 2. Map of the study area.

Fig. 3. Locations considered for study area.

Table 1. Acquired tidal current data of twelve sites with name, geographical location, and ID (TCS* = Tidal Current Site).

Station IDs	Longitude (E)	Latitude (N)	Site names	Mean spring current (m/s)	
				Flood	Ebb
TCS*1	67.352	24.775	Port bin Qasim	1.543	2.058
TCS2	67.142	24.698	Phitti Creek	1.4	1.9
TCS3	67.233	24.783	Hassan Point	1.45	2
TCS4	67.317	24.733	Jhari Creek	1.543	2.058
TCS5	67.367	24.133	Hajambro Creek	1.65	2.1
TCS6	67.45	24.15	Keti Bander	1.543	2.058
TCS7	67.301	24.353	Dabbo Creek	1.543	2.058
TCS8	67.389	24.057	Turshian Creek	1.543	2.058
TCS9	67.436	23.993	Khobar Creek	1.543	2.058
TCS10	68.04	23.754	Kajhar Creek	1.5	1.9
TCS11	68.168	23.715	Sir Creek	1.65	2.12
TCS12	67.635	23.856	Kahr Creek	1.45	2.058

continuous surfaces by taking sample points from various locations, showing an indication of better predictions. Geostatistical methods; Kriging Ordinary (KO), Kriging Simple (KS), and Kriging Universal were assessed. These models with governing equations are explicated by [24]. Results obtained from the KO method were more appropriate than the other two interpolators.

3. RESULTS AND DISCUSSION

Four different semi-variogram models; stable (STB), K-Bessel (KB), circular (CIR), and exponential (EXP) were tested for each parameter of the dataset, and model results were assessed for the best-estimated values. Estimation performance was evaluated by cross-validation method.

For the model accuracy, a cross-validation method and error estimation equations were applied [23]. The cross-validation method determines the best prediction model by evaluating that Mean Standardized Error (MSE) and Mean Prediction Error (MPE) must be minimal (approaching to zero), the Root-Mean-Square Prediction Error (RMSPE) and Average Standard Prediction Error (ASPE) should also be as minimum as possible (suitable for model comparisons), and the Root-Mean Square Standardized Prediction Error (RMSSPE) near to 1.

Figure 4 represents the outcomes of four different models STB, KB, CIR, and EXP showing an overall range of MSEC from 1.9 m/s to 2.12 m/s. It indicates that MSEC rises gradually from the creek mouth towards land and it also rises in a southeast direction (from Karachi towards Sir Creek). A comparison between the observed and estimated MSEC values is shown in Figure 5 for four models. According to this comparison, the STB model generates the lowest MSEC at TC2 (1.988 m/s) and the highest MSEC at TC9 (2.071 m/s). The CIR model yields the lowest MSEC at TC10 (1.908 m/s) and the highest MSEC at TC7 (2.075 m/s). EXP model produces the lowest MSEC at TC2 (1.980 m/s) and the highest MSEC at TC7 (2.072 m/s). KB model estimates the lowest MSEC at TC2 (1.996 m/s) and the highest MSEC at TC7 (2.074 m/s).

Analysis of Prediction Error Statistics (PES) is performed for the acceptability and the selection of a best-fitted model for MSEC. For the model validation, all PES parameters (ME, RMSE, MSE, RMSSE, and ASE) are summarized together and presented in Figure 6 for all models. Considering the conditions of validation, results obtained from the CIR model are found most appropriate and best fitted.

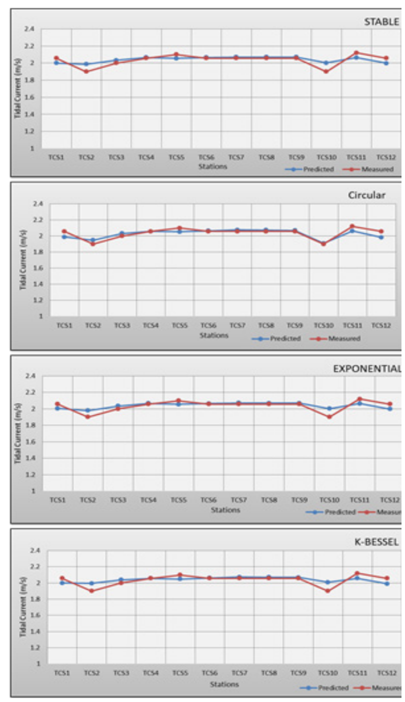

Fig. 5. Observed and predicted MSEC using different models.

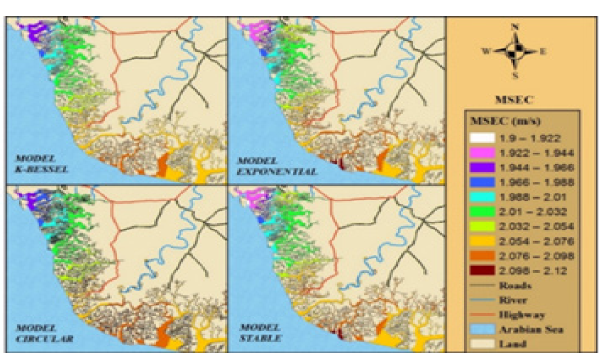

Fig. 4. MSEC models.

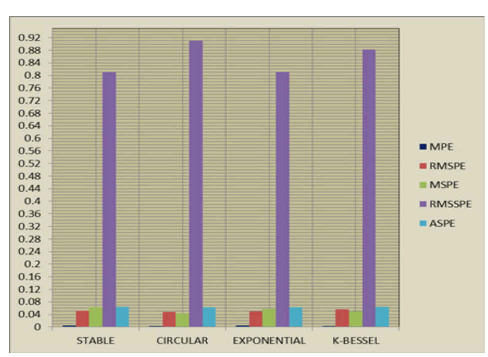

Fig. 6. Analysis for error estimation for MSEC.

Figure 7 represents results obtained from the same four models STB, KB, CIR, and EXP representing the overall range of MSFC from 1.4 m/s to 1.65 m/s. Figure 7 indicates that MSFC rises gradually from the creek mouth towards land and it also rises in a southeast direction (from Karachi towards Sir Creek). Assessment of the observed and estimated MSFC values is shown in Figure 8 for four models. According to the assessment, the STB model generates the lowest MSFC at TC2 (1.447 m/s) and the highest MSFC at TC11 (1.587 m/s). The CIR model yields the lowest MSFC at station TC1 (1.461 m/s) and the highest MSFC at TC7 (1.587 m/s). EXP model produces the lowest MSFC at TC1 (1.471 m/s) and the highest MSFC at TC7 (1.577 m/s). KB model estimates the lowest MSFC at TC1 (1.464 m/s) and the highest MSFC at TC7 (1.584 m/s).

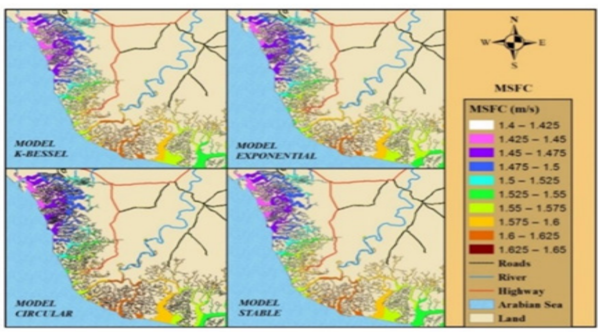

Fig. 7. MSFC models.

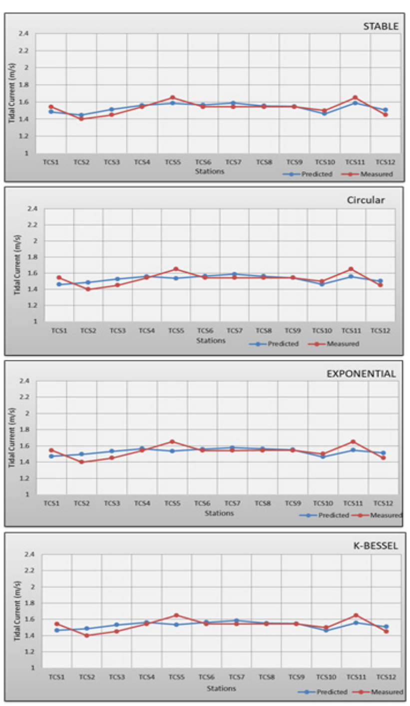

Fig. 8. Observed and predicted MSFC using different models.

Analysis of PES is performed for the acceptability and the selection of the best-fitted model for MSFC. For the model validation, all PES parameters (ME, RMSE, MSE, RMSSE, and ASE) are summarized together and presented in Figure 9 for all models. The comparative analysis shows that results obtained from the STB model are found most appropriate and best fitted.

The KO predictor is employed for the estimation of MSEC and MSFC at unobserved sites within AOI. For the prediction of data, seven more potential sites were considered where there was unavailability of data (see Figure 10). The best-fitted model is chosen (discussed and validated in the previous section) for the estimation of MSEC and MSFC. Table 2 represents estimated values of MSEC and MSFC at unobserved sites with their geographical locations.

Different layers were integrated into ArcGIS for the development of the TKPD model. These layers include MSEC and MSFC layers generated through geostatistical analysis, socioeconomic

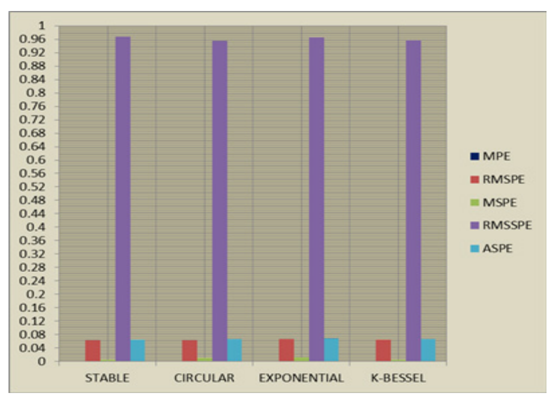

Fig. 9. Analysis of error estimation for MSFC.

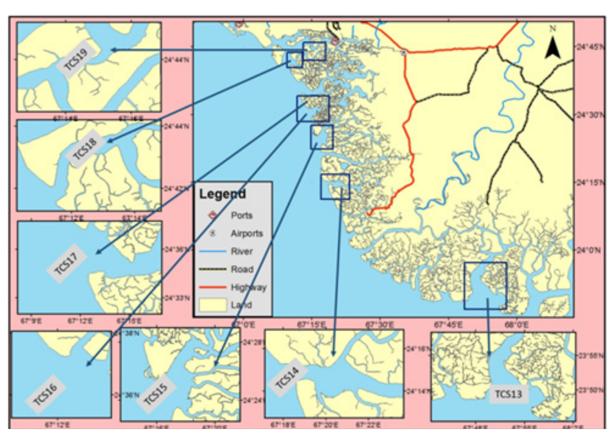

Fig. 10. Map of unobserved sites.

Table 2. Predicted MSEC and MSFC at unobserved sites.

Site (Predicted)	ID	Longitude (E)	Latitude (N)	MSFC (m/s)	MSEC (m/s)
Wari Creek	TCS13	67.85	23.9	1.588	2.078
Chan Creek	TCS14	67.3	24.24	1.51	2.035
Paitani Creek	TCS15	67.24	24.38	1.461	2.009
Khuddi 1 Creek	TCS16	67.2	24.59	1.438	1.984
Khuddi 2 Creek	TCS17	67.2	24.6	1.437	1.982
Chhan Waddo Creek	TCS18	67.2	24.7	1.446	1.969
Rakchal Creek	TCS19	67.24	24.73	1.464	1.978

layer, and eq. 1.2. Figure 11 represents the final TKPD model for MSEC and MSFC masked over the water surface which shows that the region south of the Indus Delta has substantial TKPD. Furthermore, TKPD decreases from the tail of creeks towards the mouth near the Arabian Sea. The remaining AOI is classified as having moderate TKPD.

TKPD for MSEC ranges from 1.1 to 1.6 MW/m^2 and for MSFC it ranges from 0.6 to 0.98 MW/m^2. This model is lucrative in exploring sites with prominent TKPD. Table 3 incorporates TKPD values along with the geographical locations of observed and unobserved sites.

The bathymetry model is a very essential part of tidal turbine deployment. Thus, a complete model for the best visualization of bathymetry within the study area is developed and found useful for the installation of proposed tidal turbines at a region of interest. This model shows adequate water depths at proposed sites for deployment of the tidal array structure shown in Figure 12. Regions of interest are found with depths greater than 9m. Results also show that water depths increase rapidly when moving away from creek structure that is, the mouth of creeks has larger depths than the tail of creeks.

The next step in the assessment of TSE resources in the creek region of the Indus Delta is the site selection. Criteria for site selection for TSE evaluation include the following considerations:

i. There must be significant tidal stream current which can be observed from MSEC and MSFC models.
ii. Adequate bathymetry and dimensions of the creek for deployment of MCT are required (sites with bathymetry greater than 9m are considered adequate for installation of MCT due to the size of the rotor and rated velocity of proposed MCT).
iii. The proposed site must not be a major shipping port.

In view, thirteen sites are proposed for TSE assessment by considering the above criteria. Table 4 shows the geographical locations of the proposed sites along with the dimensions of the intended creeks and their identification numbers.

To deploy an appropriate MCT that could best fit in proposed sites within AOI for power extraction; an effort was made to collect all essential information about the status of modern MCT

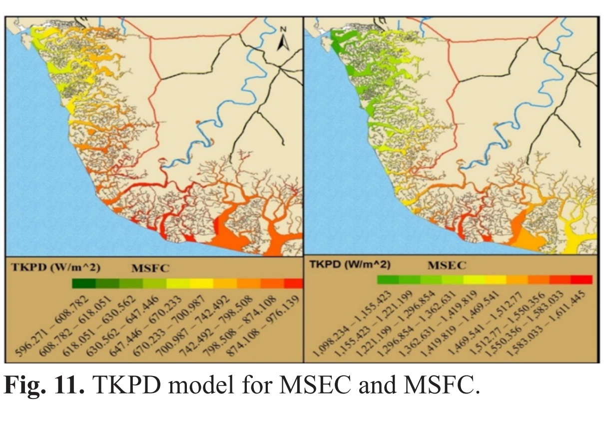

Fig. 11. TKPD model for MSEC and MSFC.

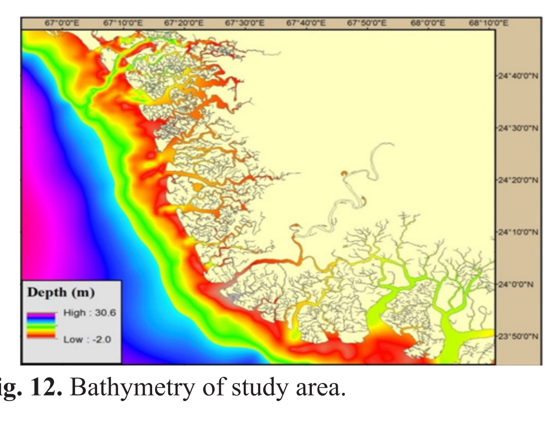

Fig. 12. Bathymetry of study area.

Table 3. TKPD (W/m^2) at observed and unobserved sites.

ID	Latitude N	Longitude E	TKPD (W/m^2)	
			(MSEC)	(MSFC)
TCS1	24.78	67.35	1420.06	798.75
TCS2	24.698	67.14	1098.23	596.27
TCS3	24.78	67.23	1260.34	662.47
TCS4	24.73	67.32	1419.79	798.28
TCS5	24.13	67.37	1581.18	976.14
TCS6	24.15	67.45	1419.79	798.28
TCS7	24.35	67.30	1419.79	798.28
TCS8	24.06	67.389	1420.09	798.80
TCS9	23.99	67.44	1420.09	798.80
TCS10	23.75	68.04	1176.68	733.39
TCS11	23.72	68.17	1611.44	976.14
TCS12	23.86	67.64	1334.21	662.47
TCS13	23.9	67.85	1521.39	873.23
TCS14	24.24	67.3	1345.19	752.8
TCS15	24.38	67.24	1251.23	680.58
TCS16	24.59	67.2	1200.72	648.39
TCS17	24.6	67.2	1198.1	647.32
TCS18	24.7	67.2	1176.65	659.06
TCS19	24.73	67.24	1218.58	684.3

Table 4. Locations where the extraction of TKE is projected.

Site ID	Latitude (N)	Longitude (E)	Length (Km)	Breadth (Km)
TCS4	24.71	67.24	4	0.23
TCS5	24.133	67.367	3	0.3
TCS6	24.15	67.45	1	0.2
TCS8	24.057	67.389	1	1.2
TCS10	23.754	68.04	4	2
TCS12	23.8556	67.635	3	2
TCS13	23.9	67.85	3	1.21
TCS14	24.24	67.3	1.9	0.148
TCS15	24.38	67.24	2	1
TCS16	24.59	67.2	5	1
TCS17	24.6	67.2	2	0.7
TCS18	24.7	67.2	4	0.58
TCS19	24.73	67.24	2	0.25

technology and their technical specifications. Some MCTs are found appropriate and compatible with site characteristics (rated velocity, bathymetry, etc.) These suitable MCTs with turbine specifications are shown in Table 5. Accordingly, a tidal array arrangement is planned with the following characteristics, as explained by [25]:

i. The lateral gap between devices was maintained at two and a half times the rotor diameter (2.5d).

ii. A row spacing of 10d was chosen. This separation is necessary to prevent adverse impacts on the downstream device's performance due to flow disturbances generated by the upstream device.

The number of MCTs needed to be installed in tidal array arrangement at proposed locations and the calculated Mean Spring Power (MSP) is determined by considering the turbine's effectiveness, seawater density, and the values of MSEC and MSFC obtained from the model findings (refer to Table 2). MSPs generated from proposed MCTs are shown in Table 6. The evaluated Mean Spring Power (MSP) produced by Verdant Power's KHPS-5 turbine is identified as the highest, reaching 2754.7 MW when compared with MSP generated from T-1 (1380 MW) and Hydro-Gen-20 turbines (2190 MW). To conclude, Verdant Power's KHPS-5 turbine is ultimately advised for deployment at the proposed locations. The Roosevelt Island Tidal Energy (RITE) Project, developed by Verdant Power in New York City's East River, was licensed for a capacity of up to 1 MW. This capacity was to be achieved through the staged installation of up to 30 turbines mounted on 10 TriFrames [26]. The MeyGen Tidal Energy Project in Scotland is a prominent tidal energy initiative with significant power generation capabilities. The project has been developed in phases, with Phase 1A involving the installation of four 1.5 MW turbines, totalling 6 MW of installed capacity. The long-term goal is to expand the project to a capacity of up to 398 MW [27].

The Indus Delta's estimated power generation capacity of 2754.7 MW far surpasses the current operational capacities of MeyGen and RITE. This is significantly higher due to the larger scale of tidal stream energy resources in the Indus Delta and the favorable tidal conditions in the region. This highlights its potential as a major tidal energy resource. While MeyGen leads in technology deployment and future scalability, and RITE demonstrates urban feasibility, the Indus Delta Creek system offers a unique opportunity for large-scale renewable energy development.

Table 5. Marine current turbines (MCTs) suggested for extraction of TKE at designated locations.

Manufacturer	MCT type	Rated velocity (m/s)	Rotor diameter (m)	Efficiency (%)	Rated power (MW)
Verdant Power	KHPS-5	2	5	44	0.035
Tocardo	T-1	2	6.3	35	0.042
Hydro-Gen	Hydro-Gen-20	2	5	35	0.020

Table 6. Projected power output from KHPS-5 marine current turbine (MCT).

ID	No. of rows	MCTs in a row	Total turbines in array	Assessed MSP (MW) using KHPS-5
TCS4	80	18	1432	68.7
TCS5	60	24	1410	77.6
TCS6	20	16	310	17.4
TCS8	20	96	1910	106.3
TCS10	80	160	12760	709.9
TCS12	60	160	9570	567
TCS13	60	97	5778	331.7
TCS14	38	12	431	22.63
TCS15	40	80	3180	157.9
TCS16	100	80	7950	379.2
TCS17	40	56	2220	105.6
TCS18	80	46	3672	173.1
TCS19	40	20	780	37.5
Total estimated output power (MW)				2754.7

4. CONCLUSIONS

This study is carried out for the exploration and estimation of TSE harnessing techniques by developing geostatistical models using GIS. AOI has so far not explored for utilization of TSE. Therefore, this research study is an initial resource estimation of TSE resources. KO method is utilized in the development of MSEC and MSFC models. Tidal stream current and satellite data are integrated with GIS to develop the TKPD model. Developed four different models show the range of MSEC varies between 1.9 to 2.12 m/s and the range of MSFC varies between 1.4 to 1.65 m/s. The geostatistical Analysis technique is utilized to analyze different interpolation methods for the prediction of MSEC and MSFC at unobserved locations. Four different models (STB, KB, CIR, and EXP) are assessed for tidal stream data. These models are evaluated and cross-validated to choose the best-fitted model for predictions of MSEC and MSFC at unobserved locations. After the evaluation of cross-validation results, a stable model is selected for MSFC, and a circular model is selected for MSEC.

The bathymetry model was developed in an ArcGIS environment to visualize and identify locations with adequate water depth for the deployment of MCT. Thirteen sites are proposed for deployment of MCT. Assessed MSP generated from Verdant Power (KHPS-5) is found highest (i.e. 2754.7 MW) when compared with MSP generated from T-1 and Hydro-Gen-20 turbines (see Table 5 and Table 6), therefore Verdant Power (KHPS-5) is finally recommended for installation at suggested sites.

5. ACKNOWLEDGEMENT

The authors would like to acknowledge Hydrography Department, Pakistan, for providing valuable support for this research study.

6. CONFLICT OF INTEREST

The authors do not have any conflict of interest.

7. REFERENCES

1. A. Rehman, H. Ma, M. Radulescu, C.I. Sinisi, and Z. Yousaf. Energy crisis in Pakistan and economic progress: decoupling the impact of coal energy consumption in power and Brick Kilns. *Mathematics* 9(17): 2083 (2021).
2. L. Jones. Five ways the Ukraine war could push up prices. (2022). https://www.bbc.com/news/business-60509453 7 March 2022.
3. NEPRA, State of Industry Report 2020, N.E.P.R. Authority, Editor, National Electric Power Regulatory Authority (NEPRA) Islamabad, Pakistan (2020).
4. M.O. Finance. Pakistan economic survey (2022) https://www.finance.gov.pk/survey_1213.html
5. J. Tao, M. Waqas, M. Ali, M. Umair, W. Gan, and H. Haider. Pakistan's electrical energy crises, a way forward towards 50% of sustain clean and green electricity generation. *Energy Strategy Reviews* 40: 100813 (2022).
6. M. Kamran. Current status and future success of renewable energy in Pakistan. *Renewable and Sustainable Energy Reviews* 82(1): 609-617 (2018).
7. T.A. Adcock, S. Draper, R.H.J. Willden, and C.R. Vogel. The fluid mechanics of tidal stream energy conversion. *Annual Review of Fluid Mechanics* 53 287-310 (2021).
8. M. Güney and K. Kaygusuz. Hydrokinetic energy conversion systems: A technology status review. *Renewable and Sustainable Energy Reviews* 14(9): 2996-3004 (2010).
9. L. Lago, F. Ponta, and L. Chen. Advances and trends in hydrokinetic turbine systems. *Energy for Sustainable Development* 14(4): 287-296 (2010).
10. M. Khan, M. Iqbal, and J. Quaicoe. River current energy conversion systems: Progress, prospects and challenges. *Renewable and Sustainable Energy Reviews* 12(8): 2177-2193 (2008).
11. M.I. Yuce and A. Muratoglu. Hydrokinetic energy conversion systems: A technology status review. *Renewable and Sustainable Energy Reviews* 43: 72-82 (2015).
12. W. Pangastuti. Study of tidal use in Seribu Islands Area. *Bsc Final Project. Bandung: Bandung Institute of Technology* (2005).
13. A. Bahaj and L. Myers. Analytical estimates of the energy yield potential from the Alderney Race (Channel Islands) using marine current energy converters. *Renewable Energy* 29(12): 1931-1945 (2004).
14. L. Blunden and A. Bahaj. Initial evaluation of tidal stream energy resources at Portland Bill, UK. *Renewable Energy* 31(2): 121-132 (2006).
15. N.S. Aziz. Tidal energy resources assessment in Indonesia: A case study in Alas Strait (2009).
16. R. Carballo, G. Iglesias, and A. Castro. Numerical

model evaluation of tidal stream energy resources in the Ría de Muros (NW Spain). *Renewable Energy* 34(6): 1517-1524 (2009).
17. A. Rashid. Status and potentials of tidal in-stream energy resources in the southern coasts of Iran: A case study. *Renewable and Sustainable Energy Reviews* 16(9): 6668-6677 (2012).
18. J. Twidell and A.D. Weir. *Renewable energy resources*. Taylor & Francis (2006).
19. L. Blunden and A. Bahaj. Tidal energy resource assessment for tidal stream generators. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 221(2): 137-146 (2007).
20. M.S. Baig, Z. Uddin, and A. Insaf. GIS-linked tidal range energy resource assessment. *Arabian Journal of Geosciences* 14(6): 1-16 (2021).
21. G.A. Mahar. Geomorphic Degradation of Indus Delta and Its Demographic Impact, University of Karachi, Karachi (2010).
22. A. Abbasi. Restoration of Sindh's primary rights over River Indus, 18th convention of SANA. *Cherry Hill, New Jersey* 4-7 (2002).
23. A. Insaf, M.S. Baig, and Z. Uddin. Tidal range energy resource assessment and power generation at Hawke's Bay and Ghizri. *Arabian Journal of Geosciences* 15(10): 1-15 (2022).
24. M.S. Baig. Estimation of Tidal Energy Utilizing Different Harnessing Techniques through Geographical Information System within Creek Area of Indus Delta, Sindh Province, Pakistan, in *Department of Applied Physics*, University of Karachi: Pakistan (2019).
25. C. Legrand. *Assessment of Tidal Energy Resource: Marine Renewable Energy Guides*. European Marine Energy Centre (2009).
26. V. Power. Roosevelt Island Tidal Energy (RITE) environmental assessment project: final report. *NYSERDA report* 11-04 (2020).
27. L.T.D. Meygen. Meygen tidal energy project phase 1 environmental statement. *Technical Report*; *MeyGen* (2012). https://marine.gov.scot/datafiles/lot/Meygen/Environmental_statement/Complete%20ES.pdf.