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Research Article

Tidal Range Energy Resource Estimation of Khor Kalmat using Geostatistical Modeling

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Abstract: Electrical power generation by tidal energy provides various advantages. The energy is highly predictable, has less impact on ecological pollution and provides an indefinite amount of renewable energy. The countries like Canada, China, Russia, South Korea and France are extensively utilizing tidal sources of energy for the generation of electrical energy. A suitable site (where less construction is required), adequate tidal range and sufficient bathymetry; are the basic requirements for the installation of a tidal power plant however sometimes there is no tidal data available for suitable sites, like Khor Kalmat tidal lagoon in Pakistan. Therefore, this study is conducted to assess the tidal energy resources of the naturally blessed lagoon, Khor Kalmat, which is located in the Baluchistan province of Pakistan, by using geostatistical modeling. A geostatistical model is developed to estimate the tidal energy potential at Khor Kalmat by using observed data of five available locations along with the coastal belt of Pakistan. Models are designed by integrating several layers into ArcGIS. These layers include tidal data, satellite metaphors and other physical and socioeconomic layers. After processing of data, digitized models and layers are generated. Five different models have been compared and the best model is carefully chosen to predict the tidal data of Khor Kalmat after validation of the individual model. During the study, it was observed that low head hydro tidal turbine of Venturi-Enhanced Turbine Technology (VETT) is best suited for harnessing tidal energy due to adequate tidal range. Consequently, by means of a bi-directional VETT device, the output power is assessed to be 269.93 MW.

Keywords: Geostatistical Modeling, Low Head Hydro Turbine, Tidal Lagoon, Tidal Potential Power Density

1. INTRODUCTION

The oceans provide an enormous and dominant source of energy and this energy can possibly be harnessed to overcome the electricity demand globally [1]. The concept of harnessing Tidal Energy (TE) is not a recent manifestation; tidal mills are being utilized since ages. However, the energy extracted was availed for mechanical movement of devices for instance to mill the grain. Ocean water prominence takes place on the earth's side facing the moon, owing to the force of gravitation. On the other side, the centrifugal force proves the same effect in opposite direction. The highest tidal amplitude (High Water HW) can be detected on the earth side where a new or full moon is observed and the lowest tidal amplitude (Low Water LW) can be detected on halfway. The tidal range describes the difference between the top to bottom level of water and it continues to move on because of the gyrations of the sun and the moon compared to the earth. The tidal range lies between 0.25 m till 10 m [2].

The harnessing techniques of TE are categorized into the following main technologies: Tidal range technology (barrage arrangements) and tidal current technology (marine current turbines). The fundamental tidal barrage model includes the structure of LH (Low Head) hydro turbines with

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gated sluices. The operating principle describes that during the HW, the water is accumulated in the region at the back of the barrage. Subsequently, the water flows out with the ebb tide. During the period of outflow, the collected water is used to rotate the tidal turbine for electricity generation.

The Tidal Range (TR) technology is different from conservative hydropower systems for electrical generation of power, in following ways: (i) In TR, water streams in both directions mean entering and leaving the barrage [3] and (ii) electrical power generation from the technology of TR is entirely anticipated. A barrage is sited through an inlet whereas a lagoon arrangement is integrated by ridges, caissons, LH turbines, ship locks and sluices gates. A dam can be built at the entering of the channel or in the centre of land-shore and island or the central of two islands (be contingent on sites) [4]. The tidal turbines can be unidirectional or bidirectional and could be of different types such as rim turbines, tubular turbines, straflo, or bulb turbines [3, 5].

The principle of the tidal lagoon works similarly to a tidal barrage. However, it reserves some part of the water relatively instead of appearing as an entire barrier over a bay. Nonetheless, it could stay within the ocean. A major difference shows that traditional barrage structure uses a regular coastline to minimize the dimension of a barrage. However, this means, obstructing the creek or estuary, irrespective of depth. On the other hand, the lagoon has a reasonably low visual impact, for the reason that it is lower than high tide water and seems identical to a common sea partition at low water tides. Lagoons could be constructed with the help of loose combinations from wrecked arrangements and excavations. Therefore to reduce the costs of construction, any combination of economically feasible materials can be used [6].

1.1 Underdeveloped TPP (Tidal Power Plant) and Tidal Lagoon

For the successful growth of the TE industry, a comprehensive study of the scope and potential of the TE resource is necessary. In comparison with lesser mature oceanic energy technologies like marine current energy, ocean thermal energy and wave energy; tidal range technologies have a long history [7]. The numerous TPPs are under progress and various feasibility studies are considering on the estimation of tidal power resources to recommend forthcoming TPP. A summary of the same is appended in table 1. In the late 1960s, Tidal energy plants have already been commercially well-designed in Canada, China and France, and most recently in South Korea [8]. In Grevelingen lakes (Netherlands), the tidal lagoon scheme will be the first of its kind Ultra Low Head (ULH) barrage, since the tidal range will merely be in lying between 50cm to 1m. Predominantly, some UK enterprises and universities are developing LH tidal systems and also in collaboration with some smaller companies in Canada and France. At Swansea Bay (UK), a 60 MW plant is proposed with a complete resource estimation of about 60,000 MW. The visual impression of Swansea Bay lagoon will also be lower than the environmental impact of the tidal barrage. In China, a 300 MW tidal lagoon plant is also contracted for installation [8].

To encounter economic crises and overcome the upcoming challenges there is an immediate requirement for the renovation of present energy resources and to develop TPPs on the coastal belt of Pakistan. For this purpose, an estimation of uninvestigated TE resources of Khor Kalmat lagoon in Balochistan province is conducted. This study is steered primarily to evaluate the TE resources of Khor Kalmat tidal lagoon for the production of electric power.

Table 1. Studies of under-progressed TPP

S.No	Location	Estimated Output Power (MW)	Impoundment Area (km^2)	Study Conducted by
1	Canada, Minas basin-Cobequid bay	4028	130	[9]
2	UK, Severn Estuary	2000	5700	[10]
3	Australia, Kimberley	3000	-	[11]
4	India, Gulf of Kutch	50	-	[12]
5	Korea, Incheon	1320	157	[13]

2. MATERIALS AND METHODS

Pakistan has around 1000 km long shoreline having naturally sanctified bays, lagoons and creeks, however, Khor Kalmat (25°27'N, 64°05'E) is considered an Area Of Interest (AOI) which is a lagoon situated near 320 kilometres west of Karachi in the central portion of Baluchistan and adjacent to Pasni. It is bounded by numerous small hills, which are the basis of siltation and sedimentation, for the period of irregular rains (figure 1). Khor Kalmat has a resemblance to the shape of a tree, from the view above ground, having its case signifying the appearance (which is a constricted 7 km long 2 km wide and around 20 m deep channel). It broadens sharply into a 19 km long and 27 km wide surrounded physique of water as an asymmetrical shape. The complete area is 102.25 km^2. Mud-Flats are generally settled in the nearly perfect lagoon, which is enclosed with superficial seawater at high tides [14]. However, even being sanctified with a natural lagoon, there is no suitable data assortment or balanced intelligence to develop the existing resources of tidal energy at Khor Kalmat.

As aforementioned, since tidal data was not available in the study area, therefore, the geostatistical method is incorporated to examine the tidal range energy resources in study area primarily.

2.1 Estimation Scheme Adopted

An estimation technique has been designed and summarized, as shown in figure 2. It comprises of succeeding steps: data acquirement, data processing, modeling in GIS, endorsement of the geostatistical model, valuation of tidal data at the overlooked site, power density calculations, identification and an assortment of appropriate tidal turbine and total tidal power valuation from the tidal turbine.

Table 2. Geographical location and station IDs of sites

Station ID	Geographical Location
1	25°07′ N 62°19′ E
2	25°16'N 63°28'E
3	25° 16' 29" N 64° 35' 10" E
4	24° 48'N 66° 58'E
5	24°47'54.6" N 67°4'56.27" E

Instruments for acquiring tidal data comprise tidal gauges and tidal poles. Data regarding TE exploration comprises sea water levels with an hour resolution for the duration of nine years (Jan 2005-Dec 2013) for five sites. Table 2 represents data acquisition sites which are classified as Gwadar, Pasni and Ormara, along the Makran coast; and Karachi and Ghizri, along the Karachi shoreline, are considered. Time series assessments of an hour of data are organized to perceive the performance

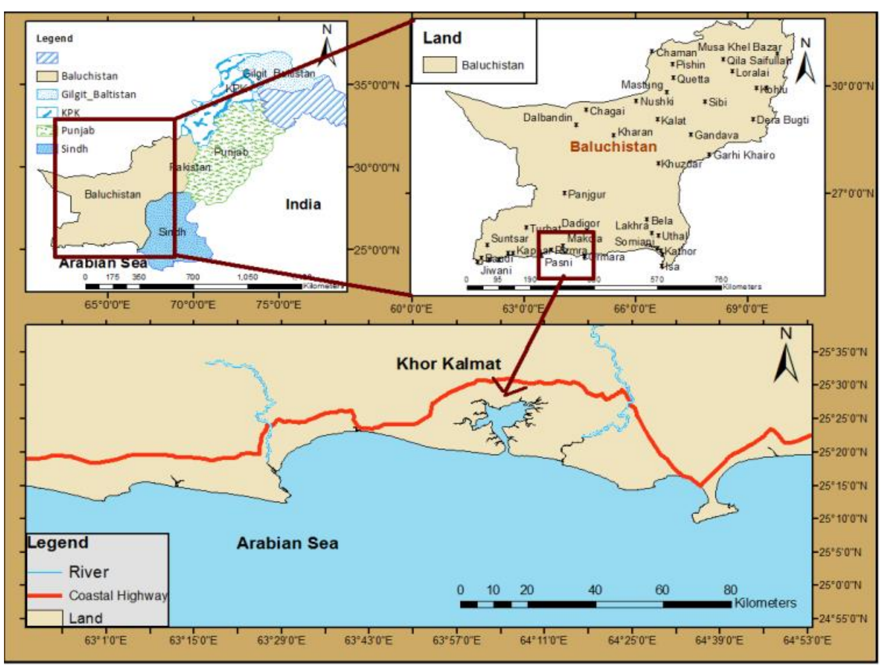

Fig. 1. Study area map

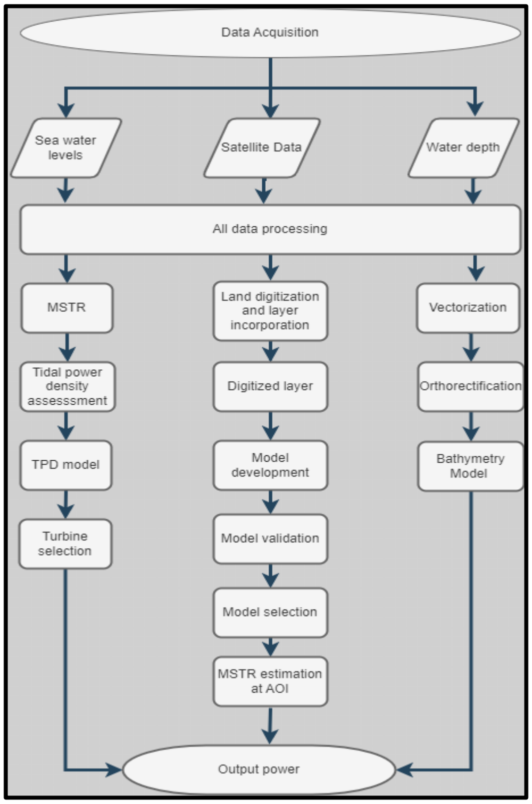

Fig. 2. Estimation methodology

of tides for the estimation of large interval trends. High and Low sea water levels were deduced to compute Mean Spring Tidal Range (MSTR). Environmental Systems Research Institute (ESRI) was retrieved for satellite data [15] and bathymetry data was attained from Hydrography Department, Pakistan [16].

2.2 Validation Method

A cross-validation method was applied to verify the model's accuracy. This method governs the selection of the best model by evaluating statistical error measures. Statistical error measures require the following conditions for the selection of the best model as explained by [17].

1. Root Mean Squared Errors must be small (RMSE)
2. Mean Errors close to zero (ME~0)
3. Mean absolute error (MAE) near to RMSE (MAE ~ RMSE) and both must be small
4. Normalized RMSE must be close to 1 (NRMSE~1)

2.3. Power Density Model

As per [18], potential energy per tide can be assessed as:

$$E = 0.5A\rho g h^2 \text{ (Energy per tide)} \quad (1)$$

Where,

E = Energy per tide
A = area (m^2)
ρ = density of seawater (around 1025 kg/m^3)
g = Acceleration due to gravity (9.8 m/s^2)
h = tidal range (m)

For one tidal period t, mean power (potential) can be computed as:

$$P(mean)=(A\rho g h^2)/2t \quad (2)$$

For semi-diurnal tides, there are 2 high and low tides. Thus, mean power observed in a day = ($A\rho g h^2/2t$) x 2

$$P=(A\rho g h^2)/t \quad (3)$$

Hence power density derived from potential energy is evaluated as:

$$P.D._{PE}=(\rho g h^2)/t \quad (4)$$

Power generation using an appropriate tidal turbine can be assessed by using the following relation:

$$P=\rho\times g\times Q\times H\times\eta \quad (5)$$

Where,

P = Power generated by a turbine (MW)
Q = Discharge (m^3/s)
H = Water level (m)
η = Efficiency coefficient of turbine

3. RESULTS AND DISCUSSION

3.1. MSTR Model

The MSTR model for AOI was developed by integrating thematic and other layers into the ArcGIS environment. The MSTR model included

MSTRs and physical layers extracted from satellite data, socioeconomic layers (identifying major cities, transportation network, airport, seaport, highways, rivers, fish harbors locations, grid stations and power plants along Makran coast as shown in figure 3).

Geostatistical interpolators; Simple Kriging (SK), Ordinary Kriging (OK) and Universal Kriging (UK) were examined in this study. Results obtained from SK interpolators were found well-fitted and therefore SK interpolators were opted for the development of semi-variogram models. Stable, Spherical, Hole-Effect, Circular and J-Bessel were analyzed (abbreviated as spherical=SPH, circular=CIR, stable=STB, J-Bessel=JB, and hole-effect=HE) and used for the estimation of MSTR at AOI. MSTR models were developed by incorporating STB, SPH, HE, CIR and JB semi-variogram techniques as are shown in figure 4.

Estimated MSTR was compared with observed MSTR for validation purposes and presented in figure 5, demonstrating the results of five models. Developed MSTR models were validated by evaluating statistical error measures of MSTR (shown in figure 6). By considering the conditions of validation as described in section 2.2, it is determined that the CIR model was found best for accomplishing the requirement of the cross-validation method. The implication is that the CIR model is preferred for the assessment of MSTR and is opted to predict MSTR at AOI. The estimated value of MSTR at AOI is assessed as 1.932m.

3.2 Bathymetry Model

The Bathymetry model is necessary for the deployment of tidal turbine and impoundment area calculations. Thus, a comprehensive model for the best visualization of bathymetry for AOI is developed. This model shows adequate water depths in the range of 3.1 to 20.6 m at the proposed lagoon as shown in figure 7.

3.3 Tidal Power Density (TPD) Model

TPD model was established by integrating the MSTR layer, equation 8, physical layer and socioeconomic layer (identifying major cities, transportation networks, airports, seaports, highways, rivers, fish harbors locations, grid stations and power plants along Makran coast as shown in figure 8) into ArcGIS environment. TPD model highlights areas comprising of high and low potential densities ranging between 0.746 W/m^2 to o 1.25 W/m^2. TPD of lagoon lies within the range of 0.818-0.854 W/m^2.

After analytical analysis of this study, it is observed that AOI is encompassing significant MSTR, ample water depth and natural lagoon structure (requiring less civil construction cost). Therefore, Khor Kalmat is considered as the best region for harnessing tidal energy. Finally, the assessed power output (using equation 5 and η=1) is evaluated to be 589.6 MW as mentioned in table 3.

Fig. 3. All layers presented as a combined secondary layer for the development of MSTR model

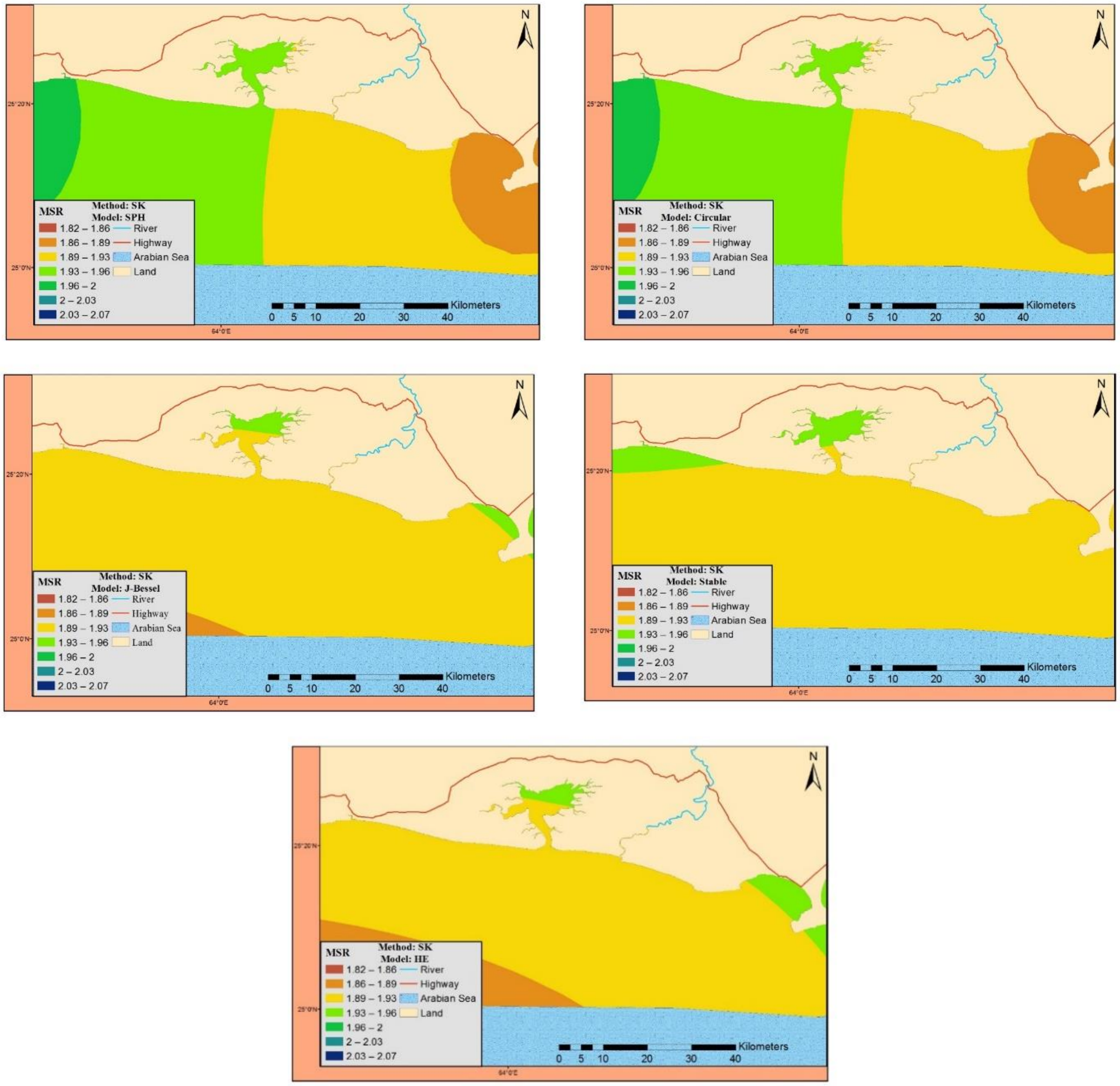

Fig. 4. Geostatistical models for estimating MSTR

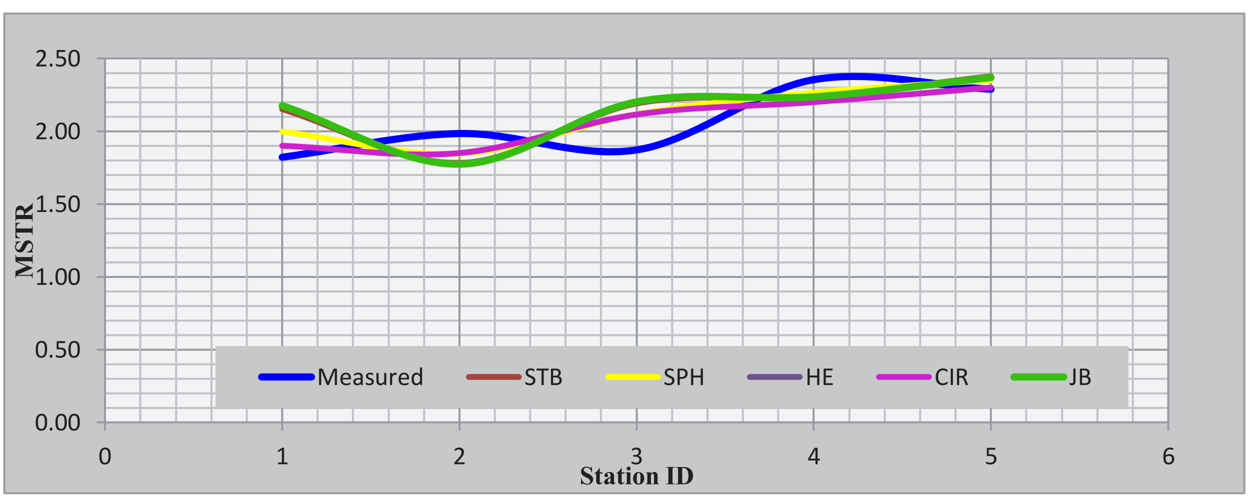

Fig. 5. Measured versus estimated values of MSTR from different models

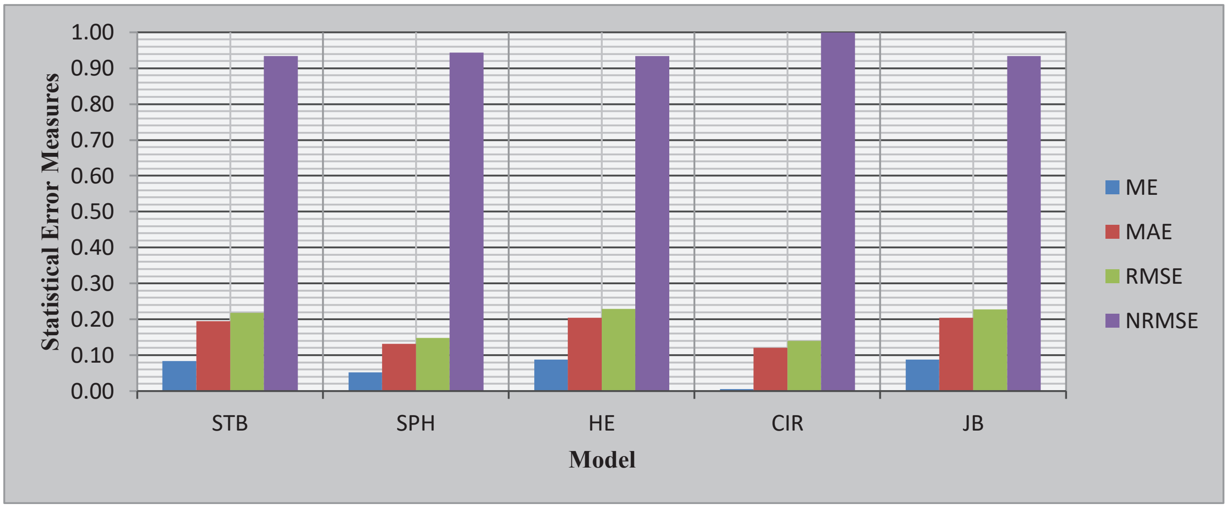

Fig. 6. Statistical error measures

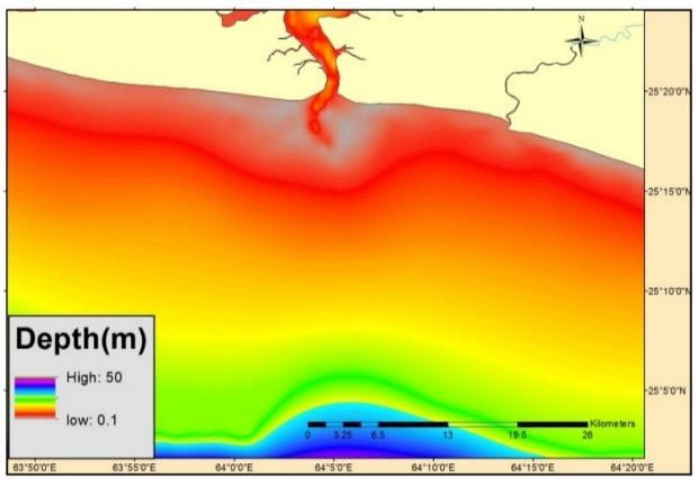

Fig. 7. Bathymetry map study area

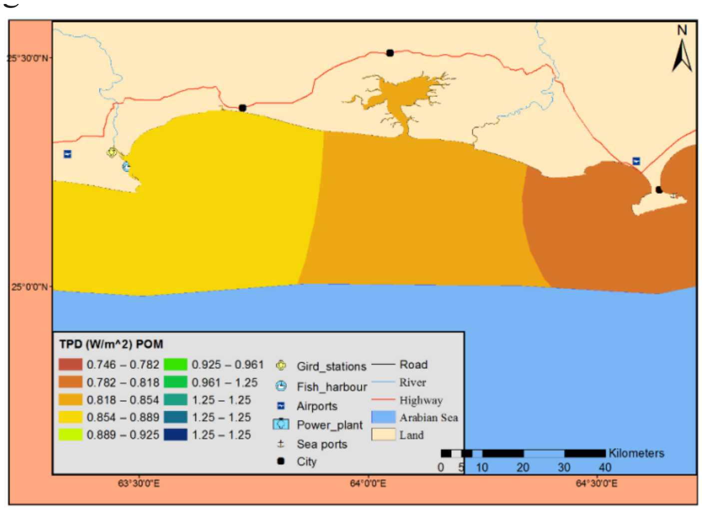

Fig. 8. TPD (W/m^2) of nine years averaged data

Table 3. Assessed tidal power

AOI	Impounded Area (km^2)	Discharge (Q) (m^3/s)	Power Output (MW)
Khor Kalmat	226.21	30349.84	589.6

3.4 Output Power

Since a moderate tidal range is observed in the study area therefore the study is focused on LH tidal turbines. The main factors of tidal energy generation depend upon size of the tidal pond, tidal range (i.e. head size for turbine) and choice of turbines. The evaluation can be carried out with the help of equation 5.

The selection of a suitable/appropriate turbine would be vital for harnessing tidal energy along with maximum power output. Owing to this, a detailed and conclusive review of latest tidal turbines has been conducted. The technology being used in VLH turbines are found to be the latest one and the movable housing of VLH turbines includes the arrangement of a propeller turbine along with a built-in generator [19].

The proficient method to synchronize VLH sources to conventional turbines is Venturi-Enhanced Turbine Technology ('VETT'). It can also increase the cost-effectiveness of traditional turbines used for the generation of electrical power from VLH sources. VETT uses venture to strengthen head drop through its turbine [20]. Due to this, the VETT turbine was noted to be the most appropriate for the study area. Table 4 depicts the width of the channel region and the area of tidal confinement. The installation configuration of the VETT device can be possible in either unidirectional or bidirectional moreover the study proposed bidirectional installation. The bidirectional installation is advantageous for the study area because the turbine works with both tides (ebb and flood) with sluicing taking place during times of low water and high water. Therefore, it is expected that four hours per tide generation is possible using the bidirectional installation. The optimal head is required for the generation whereas the startup head for the VETT device is 0.5m. Finally, the total estimated power for the study area is 269.93 watts.

4. CONCLUSION

The rationale of this research is to assess the tidal range energy at tidal lagoon of Khor Kalmat (study area) by incorporating geostatistical modeling. This tidal lagoon of Khor Kalmat was never explored before, for the study of tidal energy. Subsequently, this study provides the preliminary estimation of TE resources. Moreover, the tidal data of Khor Kalmat tidal lagoon was also not available. Therefore, the geostatistical model was developed by utilizing observed data from five available locations for the prediction of MSTR at Khor Kalmat. The moderate tidal ranges as well as a suitable environment were observed for the generation of tidal energy. Satellite imagery was used to complete the above-mentioned tasks with the land imagery digitized into line, point and polygon structures along with further socioeconomic data. The ArcGIS 10.1 software was accessed to digitize the data. The Geostatistical Analysis tool was used to develop MSTR models with the help of incorporated layers. Subsequent to multiple times evaluations and cross-validation of the MSTR model, the prediction of MSTR at Khor Kalmat took place. The identifying areas of sluices, turbine installation and tidal impoundment were carried out through the development of Bathymetry models.

Moreover, depth identification for tidal turbine installation was possible with the help of the Bathymetric model. The potential of tidal lagoon

Table 4. Tidal power plant calculations at AOI

AOI	Impounded Area (km^2)	Sluice width (km)	Q_t (m^3/s)	Turbine type	No. of turbines	Efficiency	Estimated output power (MW)
Khor Kalmat	226.21	2.26	206	VETT	144	65%	269.93

for tidal power generation has been analyzed by the TPD model. The estimated theoretical output power is 589.6 MW. Keeping above points in view, it is concluded that the installation of bidirectional VETT turbines at the tidal lagoon will be suitable to provide 269.93 MW of tidal output power.

5. CONFLICT OF INTEREST

The authors declare no conflict of interest.

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