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SUITABILITY ASSESSMENT OF WIND ENERGY FARMING IN THE DESERT LANDSCAPE OF ZARAFSHAN VALLEY, UZBEKISTAN

ABSTRACT

Wind farm suitability analyses have been carried out to demarcate the potential zones in the Middle Zarafshan River basin. Uzbekistan's major cities occupy the middle and lower Zarafshan Valley, which needs to allocate and develop wind energy farms to restore sustainability. In the current study, the Middle Zarafshan valley was assessed to provide a synoptic view of potential zones for wind energy. This study aimed to develop a geospatial method to identify optimal locations in the valley. To accomplish this task, five criteria were considered: wind speed, slope, distance from the transmission network, road network, land use, and land cover. Further, each criterion was assigned a weight according to expert opinions and published research outcomes. In addition, a maximum of 45 % weight was assigned to wind speed, followed by land use, land cover, slope, and others. Further, these criteria were categorized into four classes viz., unsuitable, less suitable, moderately suitable, and highly suitable. Further, different thematic layers were produced to realize this study. Wind speed maps were derived at different heights to calculate the results and integrate them with other derivatives. The findings of this study show that the maximum intensity of winds received at 100 m height or more, and more than 40 % area of the study area was estimated suitable for wind energy exploitation.

KEYWORDS: wind energy, renewable energy, suitability analysis, Zarafshan Valley, Arid Region, GIS

INTRODUCTION

Growing carbon emissions, increasing population and depletion of fossil fuels increase pressure and create a significant challenge for humanity to develop an alternate and sustainable energy resource [*Abas* et al., 2015; *Roehrkasten*, 2015; *Singer* et al., 2017; *Whiting* et al., 2017; *Barreto*, 2018; *Xu* et al., 2019; *Kahatapitiya* et al., 2022]. The energy demand has increased manifold in the last decades and this growth seems to continue with fossil fuels providing the majority of this energy. However, manifestations of burning fossil fuels are being witnessed worldwide in the form of serious environmental problems including carbon emissions, air pollution, and climate change. It means that current energy trends are not sustainable and a better balance must be found between energy security, economic development, and protection of the

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environment. Therefore, it needs an alternative source of sustainable energy like wind. Wind is a plentiful natural resource that can be harnessed by mechanically converting wind energy to electricity with the aid of wind turbines [*Ahmed* et al., 2004; *Shata* et al., 2006]. Further, wind energy is explained by Ackermann and Soder [2002]. It has plentiful potential and comes from nature including tidal, wind, solar, and geothermal [*Baydyk* et al., 2019; *Chamundeswari* et al., 2021; *Rahman* et al., 2022]. Non-conventional energy achieves two goals: decarbonizing the energy supply chain and supplying energy to meet rising demand [*Li* et al., 2020; *Laldjebaev* et al., 2021]. On this topic, several researchers have worked on it. However, studies at the national level are more prevalent than evaluations at the regional level in this area. For instance, regional-level studies conducted in Africa have examined the potential, deployment status, and elements of renewable energy [*Bugaje*, 2006; *Brunet* et al., 2018; *Da Silva* et al., 2018], user interactions with technology [*Amuzu-Sefordzi* et al., 2018], and development and policy [*Aliyu* et al., 2018; *Ouedraogo*, 2019]. In Europe, there have been numerous devoted studies on the condition of energy resources, the development of renewable energy goals, and the efficacy of policy instruments [*Bersalli* et al., 2020].

Central Asia has the potential to effectively harness wind energy. Nonetheless, a comprehensive analysis of unconventional energy resources is uncommon in this area. A comprehensive examination of non-traditional energy in Central Asia is provided by Shadrina [2020] whereas Kazakhstan was studied more thoroughly than Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. According to UNIDO and ICSHP [2016], Uzbekistan has a 1 600 MW wind energy potential. Avezova and co-researchers estimate wind potential at over 1 GWh [*Avezova* et al., 2017] while Kochnakyan and others jump it up to 4652 GWh [*Kochnakyan* et al., 2013]. It indicates that Uzbekistan has a considerable amount of wind energy potential, which needs detailed analysis using modern technologies in a precise and effective manner. This study focuses on estimating wind energy suitability zones in the middle Zarafshan River basin using geospatial technology. Geospatial technology is being used as a vital tool for assessing different non-conventional energy resources worldwide. As per UNDP, Uzbekistan has the potential to produce 1 600 MW of wind energy annually [UNDP, 2014]. Therefore, this study classifies the various criteria and assigns them weights to delineate viable wind energy farming zones.

RESEARCH MATERIALS AND METHODS

Study Area

Fig. 1 shows the location of the study area, which is formed by the deposition by the Zaravshan River. Upper Zarafshan Valley consists of mountains, piedmont zones, alluvial fans, and deep valleys while the middle Zarafshan Valley is dominated by nearly plain areas, low hills, and shallow & broad-floored valleys. In the north, the river carves low hills which demarcate basin boundaries. Further, this river divides into two parts, i. e. Akdarya and Karadarya.

Typically, winds range in speed from 4 to 15 m/s and blow from west to east before making a little shift to the south. It indicates that middle Zarafshan has a significant capacity to harness wind energy and provide carbon-free electricity for a variety of purposes. The climate in Uzbekistan is dry and continental (classified as Arid Region), with significant day-to-day and seasonal temperature changes. Flat topography dominates the country while the southeastern region is carved of highly elevated mountainous terrain like Tashkent (Tien-Shan) and Samarkand. Summers are long, hot, and dry with an average monthly temperature from 27.2 °C to 35 °C. Winters are cold with an average monthly temperature between −1 °C and −3 °C.

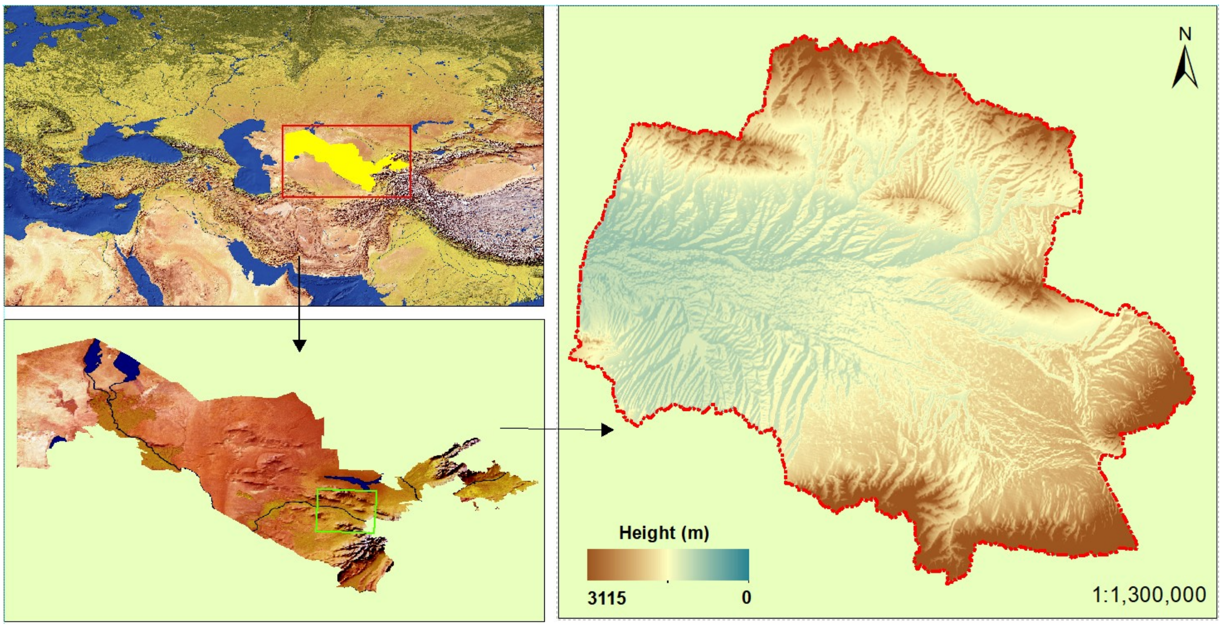


Fig. 1. Location of Study Area

Factors for Wind Power Suitability Analysis

The most important factor for establishing a wind farm or wind turbine is wind power. In this sense, Central Asia has a strong potential to locate new wind farms. However, wind turbine sites require many factors to evaluate before choosing a site. The efficiency of wind turbines depends on wind speed dominantly [*McWilliam* et al., 2012; *Aktas*, *Kabak*, 2016; *Adedeji* et al., 2021]. However, many factors influence the suitability of an area for setting up wind farms. These factors are distance from a road, distance from a transmission line, and slope of the area of interest. Previous studies confirmed that wind farms should not be located 10 km away from the road network [*Amarsinghe*, *Perera*, 2021]. Distance from the urban centers is also considered an important criterion. This criterion was considered in the land use and land cover classes. For this study, only non-populated areas were considered suitable. Further, the elevation creates technical issues for wind energy potential, as well as the cost of installation and maintenance. Practically, top of hills (rounded), open plains, and gaps in coastal mountains are best suited for wind power generation due to the availability of consistent and reliable winds [*Amarsinghe*, *Perera*, 2021]. Slope is another important parameter that influences wind potential and turbine stability. The apex of steep slope winds does not hit the turbine rotor at a perpendicular angle, resulting in increased fatigue for the turbine [*Pao*, *Johnson*, 2009; *Hyvärinen*, 2018; *Katsaprakakis* et al., 2021]. In addition, a value greater than a 5-degree slope will interfere with the stability of the turbine and give more turbulent wind patterns.

Data and Methods

Sentinel-2 and Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model were used in this study; they were both retrieved from online distribution services and were made available at Global Copernicus Open Access Hub[1] and NASA Earth data[2] platforms, respectively. Both datasets were obtained, and preprocessing was done to set up various thematic layers for relevant information extraction. To determine a drainage network

[1] Global Copernicus Open Access Hub. Web resource: https://scihub.copernicus.eu (accessed 12.06.2023)
[2] NASA Earth data platforms. Web resource: https://search.earthdata.nasa.gov/search?portal=idn&fi=ASTER (accessed 12.06.2023)

and watershed, the first digital elevation model (DEM) was integrated into a GIS system [*Farooq* et al., 2015]. The middle Zarafshan Valley, the area of interest, was also defined using the watershed. Further, the digital elevation model was used to generate the slope layer. Road networks and transmission lines data were collected by digitizing on Google Earth and from country statistics agencies, respectively. Land Use & Land Cover (LULC) derived from ESA Sentinel-2 imagery at 10 m resolution. The underlying learning method uses 4 bands of Sentinel-2 surface reflectance data, i. e. blue, (B2 490 nm), green (B3 560 nm), red (B4 665 nm), and near-infrared (B5 705 nm) bands with given central web lengths. To obtain the final result, a traditional approach of supervised image classification was steered with the help of GCP information collected during the field survey, and then a final representative map was composed in ArcGIS Software for the year 2022 (October). Further, Fig. 2 and Table 1 show the flowchart of the methodology and rationale of the study along with data used in the present study.

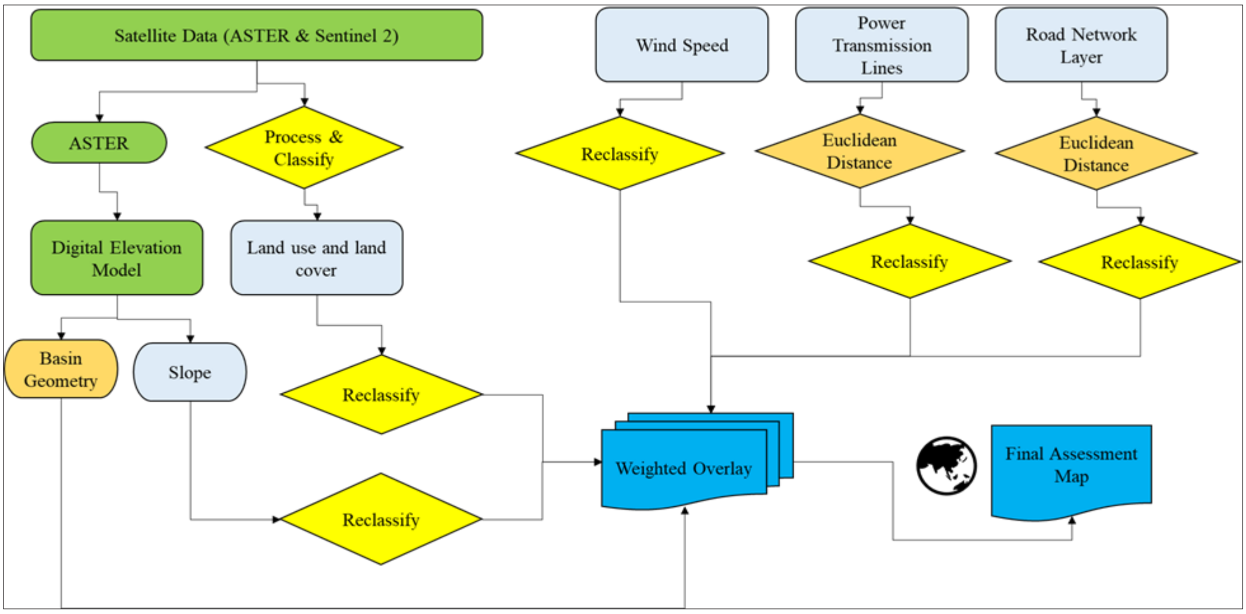


Fig. 2. Flow diagram of the methodology used in the present study

Table 1. Rationale and data used in the study area

Indicator (Data Layer)	Data Source	Rationale for selection	Data Type	Spatial Resolution
Wind speed	*Neil* et al., 2023	Constant availability of wind speed is essential for wind energy production	Raster	250 m
Slope, degree	ASTER DEM	Slope affects the development and construction activities of wind power infrastructure	Raster	30 m
Land use and land cover	Sentinel 2 satellite products	Land use is an important aspect of any type of development activity due to the suitability of land for various purposes	Raster	10 m
Distance to Transmission	OSM; Ministry of Energy, Uzbekistan	Utilization of existing transmission lines and viable investment in new transmission lines	Vector	Polyline
Distance to Road	OSM; Google Earth	Considering accessibility and minimizing the investment in construction and operation costs	Vector	Polyline

Further, the classified layer was categorized into 6 classes viz., water, vegetation, cropland, built-up, bare land, and rangeland. In the classification scheme water refers to rivers, ponds, lakes, and open water bodies surface, whereas vegetation includes both dense and sparse parcels of naturally grown land cover. Cropland was classified by considering all types of agricultural land, viz. irrigated and rainfed of both cereal and broadleaf types of agricultural practices. The built area includes urban and built-up areas with artificial surfaces, impervious surfaces, buildings, residential and commercial structures, asphalt, and associated areas. Further, the bare area was marked with rock or soil, large areas of sand, deserts, exposed rock, dry salt flats/pans, dried lake beds, etc. without or with very sparse to no vegetation for the entire year. The sixth category of land cover was rangeland, which includes all open areas covered in homogenous grasses, scrubs, or no taller vegetation. It also includes some cases of mixing small clusters of dispersed plants with exposed soil or rock. It is an important parameter in determining the suitability of land for wind energy farming as different land use and land cover classes as well as infrastructure facilitate the selection of potential wind energy farming sites/locations in more than one way. Further, to demarcate the potential zones of wind energy suitability, the following parameters have been derived and given suitable weights as per Table 2.

Table 2. Selected Parameters and their relative weight for assessing the suitability of wind energy farming locations

Sr. No.	Criteria	Weight (%)	Factors	Suitability
1	Wind Speed (range 3–12.41 m/s)	0.45	3–6 (m/s)	Unsuitable (1)
			6–7	Low Suitable (2)
			7–9	Moderate Suitable (3)
			>9.0	High Suitable (4)
2	Slope, degree	0.1	0–2	High Suitable (4)
			2–5	Moderate Suitable (3)
			5–8	Low Suitable (2)
			>8 %	Unsuitable (1)
3	Distance to Transmission (m)	0.15	0–5 000 m	High Suitable (4)
			5 000–10 000 m	Moderate Suitable (3)
			10 000–15 000 m	Low Suitable (2)
			>15 000 m	Unsuitable (1)
4	Distance to Road (m)	0.1	0–500 m	Low Suitable (2)
			500–5 000 m	High Suitable (4)
			5 000–20 000 m	Moderate Suitable (3)
			>20 000 m	Unsuitable (1)
5	Land use & land cover	0.2	Rangeland	Suitable

After generating all thematic layers, they were modeled for weighted overlay analysis in ArcGIS software to obtain the desired outcomes. Based on this output layer, wind energy suitability zones were described in the Middle Lower Zarafshan Valley.

RESEARCH RESULTS AND DISCUSSION

Results are shown separately and combined with other thematic layers to create the final product. A few important layers were derived to demarcate potential zones of wind energy farming in the Middle Lower Zarafshan valley.

Wind Speed

Wind speed results were derived for estimating varying speeds in the middle lower Zarafshan valley at heights about 50, 100, 150, and 200 m above the ground. It indicates that the Zarafshan Valley feels different wind intensities at varying heights. At 50 m, 71.94 % of area of the middle Zarafshan Valley experiences low-intensity wind (less than 6 m/s) and 23.38 % of area experiences higher wind velocity between 6–7 m/s while approximately 5 % of area experiences strong winds. It was also observed that as the height increases, wind speed increases. At 100 m, the strong winds area expanded significantly and covered more than 67 % of the study area. It indicates that 100 m in height is comparatively more suitable. At 150 m, 84.05 % of area of the middle Zarafshan Valley experiences potential winds, available for generating wind energy. It increases from 50–100 m while it decreases from 100–200 m. At wind speed between 7–9 m/s, it increases from 50–150 m while it decreases from 150–200 m. For wind speed >9 m/s, it shows an increasing trend with height continuously. It is observed that wind speed data indicates different trends of potential and spatial distribution of wind intensity (Table 3). For example, 71.94 % of the area is covered with low-intensity winds, which is less suitable for low-height wind turbines. One interesting fact observed is that flat and populated areas experience slow wind (Fig. 3a wind speed at 50 m) while increasing height is proportional to the wind speed.

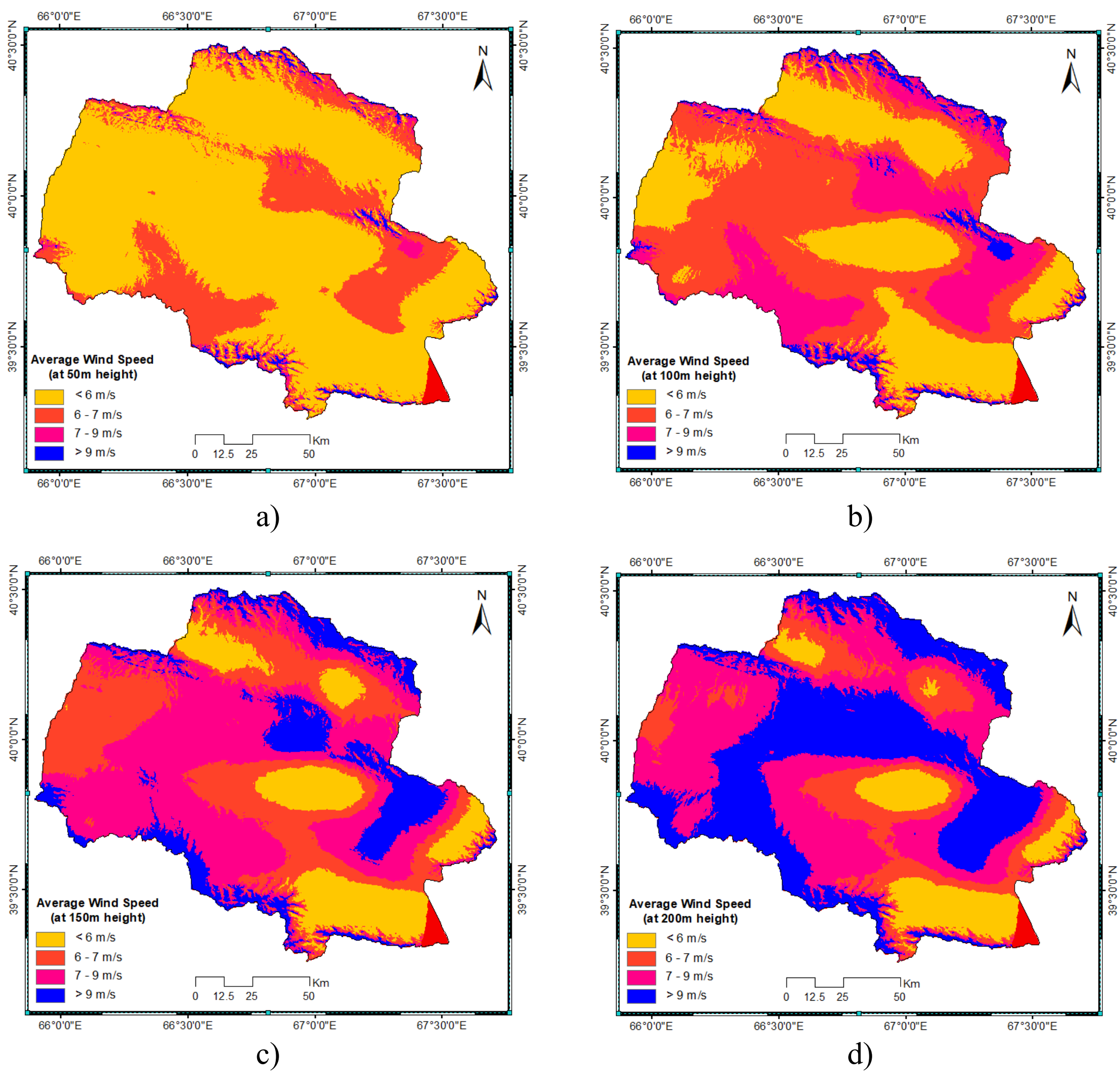


Fig. 3. Spatial distribution of wind speed at varying heights (a–d) at 50, 100, 150, and 200 m

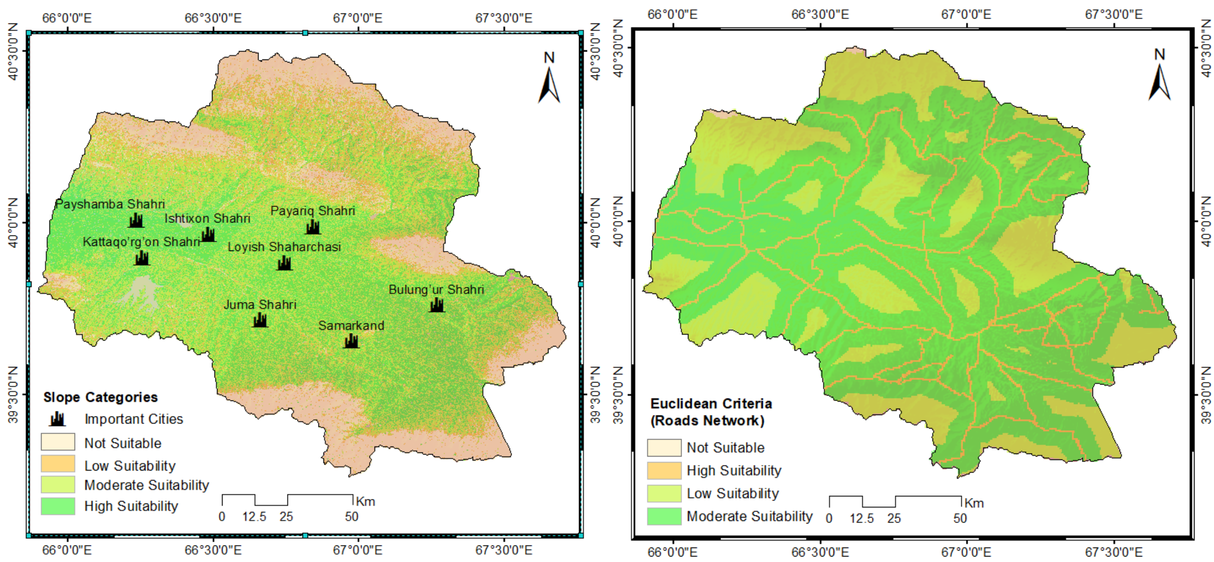
Table 3. Statistics of wind speed under different speed categories

Wind Speed (m/s)	**<6**	**6–7 m/s**	**7–9 m/s**	**>9**
Wind Area (at 200 m)	1430.44	2152.06	4665.65	4495.21
	11.23 %	16.89 %	36.61 %	35.27 %
Wind Area (at 150 m)	2032.25	3657.96	5115.44	1937.71
	15.95 %	28.70 %	40.14 %	15.21 %
Wind Area (at 100 m)	4160.34	5225.10	2845.08	512.85
	32.65 %	41.00 %	22.33 %	4.02 %
Wind Area (at 50 m)	9167.75	2979.52	409.74	186.35
	71.94 %	23.38 %	3.22 %	1.46 %

Source: authors' estimate

Slope

The east-west trending middle Zarafshan valley consists of different slope categories that make it more suitable for wind energy potential in general. The results of this study exhibit some interesting facts. The central part of the middle Zarafshan Valley is almost flat and highly suitable for wind turbine installation. However, the boundaries of the valley (Northern and Southern areas) are not suitable for installing wind turbines due to the steep slope and high cost of installation. Out of the total study area of the valley, almost 34 % of area was flat with less than a 2° slope, while more than 35 % was almost plain with a slope ranging from 2° to 5°. This means that approximately two-thirds of the study area was suitable for setting up wind energy infrastructure from the slope perspective. Fig. 4a shows the spatial distribution of slope under different categories.



a) b)

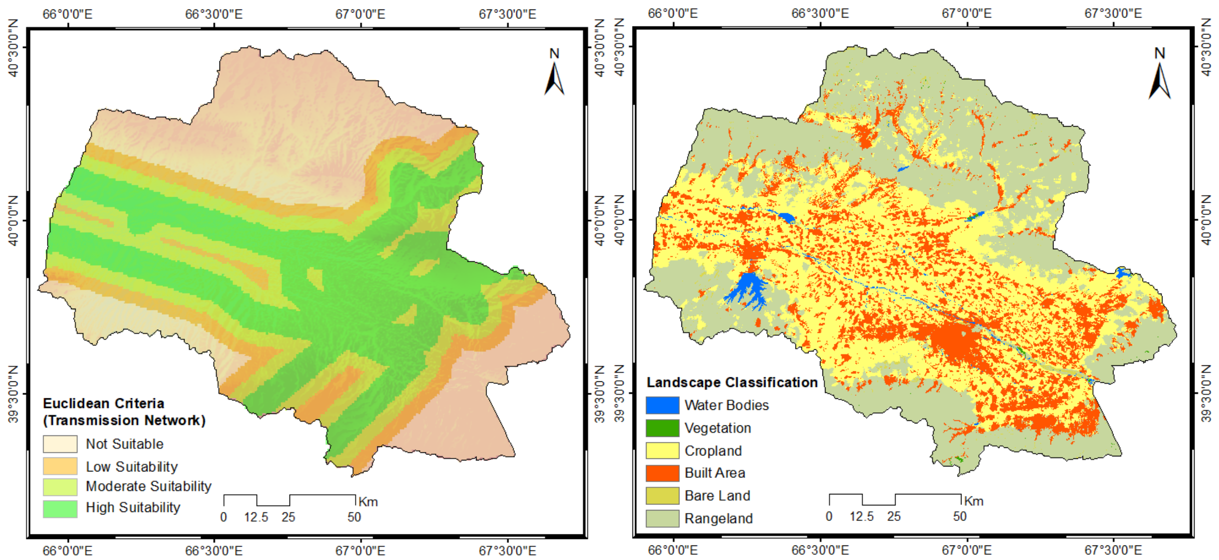
Fig. 4. Spatial distribution of slope and road network (a & b) — Euclidean distance

Distance from Road Network

The road network layer was draped over other layers to analyze the distance between potential areas, and the road network. Further, suitable areas were extracted into four categories viz., highly suitable, moderately suitable, low, and not suitable (Fig. 4b). The results of this analysis show that 6.75 % and 29.07 % of areas are under highly suitable and moderately suitable classes respectively, while 63.99 % and 0.19 % of areas are under low suitability and not suitable. It indicates that the road network needs more proliferation at the ground to provide the necessary support for converting low-suitability areas into highly suitable areas.

Distance from Transmission Network

The transmission network is one of the important parameters for the distribution of wind-generated energy from the source to users. Therefore, it makes sense to develop a system in which wind turbines and transmission networks share a common tower. For this purpose, the transmission network was studied and categorized into four classes viz., the transmission network less than 5 km away from suitable areas, 5–10 km, 10–15 km, and more than 15 km away (Fig. 5a). In this sense, results were studied and forwarded many remarkable facts. If the transmission network and wind farms are close-spaced (less than 5 km), there will be minimum loss of energy and it will be cost-effective. There will be less environmental impact as well.



a) b)

Fig. 5. Spatial distribution of power transmission network and land use land cover (a & b)

Land Use and Land Cover

Results of land use and land cover indicate that the Middle Zarafshan Valley displays a mosaic of vegetation, barren, rangeland, built-up, and cropland (Fig. 5b). Out of a total of 12 743.40 km^2 selected area, the highest share of land cover was classified into rangeland of about 5 341.1 km^2 followed by cropland (4 825.2 km^2), urban built up (2 321.1 km^2), water bodies (125.5 km^2), bare land (118.4 km^2), and natural vegetation (12 km^2) in the study area. For establishing the wind turbine, LULC analysis reveals some distinguished facts [*Shakir* et al., 2018; *Suhail* et al., 2019] that rangeland and bare land are the most suitable areas in the middle Zarafshan Valley, which accounts for more than 42 % of the total study area. The Samarkand Region occupies most of the middle Zarafshan valley. The Samarkand city is densely populated, especially along both banks of the Zarafshan River.

Wind Energy Farming Suitability Zonation

In this study, suitability maps were generated at various heights using five key parameters: wind speed, slope, proximity to transmission lines, distance to road networks, and land use/land cover. These criteria were carefully integrated and weighted according to established standards to ensure accuracy and relevance. The analysis resulted in the classification of wind energy potential zones into four categories: not suitable, low suitability, moderate suitability, and high suitability. This categorization provides a clear framework for identifying regions with optimal conditions for wind energy development, offering a practical tool for decision-makers and planners in the energy sector.

At a height of 200 m, the total area classified as unsuitable for wind energy farming was 7 283.4 km^2, representing 58.44 % of the entire study area. The area considered less suitable measured 215.35 km^2, or 1.73 % of the total. Moderately suitable land was estimated at 1 757.39 km^2, accounting for 14.10 %, while the highly suitable category covered 3 207.15 km^2, equating to 25.73 % of the region. These figures suggest that the middle Zarafshan Valley offers significant potential for wind turbine installation.

At 150 m in height, the unsuitable area remained consistent at 7 283.84 km^2 (58.44 % of the study area). However, the less suitable area increased to 380.71 km^2, accounting for 3.05 %. Moderately suitable land expanded to 2 982.83 km^2, covering 23.93 % of the total area, while highly suitable land decreased to 1 816.36 km^2, or 14.57 %. This reveals that as height decreases, suitability for wind farming reduces, although the amount of moderately suitable land increases (Table 4). These findings provide valuable insights for optimizing the selection of wind energy zones at different heights.

Table 4. Statistics on the suitability of wind energy farming area

Height (amsl)	Not Suitable	Low Suitability	Moderate Suitability	High Suitability
Suitable area (at 200 m)	7 283.84	215.35	1 757.39	3 207.15
	58.44 %	1.73 %	14.10 %	25.73 %
Suitable area (at 150 m)	7 283.84	380.71	2 982.83	1 816.36
	58.44 %	3.05 %	23.93 %	14.57 %
Suitable area (at 100 m)	7 283.84	736.21	3 557.09	886.61
	58.44 %	5.91 %	28.54 %	7.11 %
Suitable area (at 50 m)	7 283.84	1 692.87	3 211.42	275.61
	58.44 %	13.58 %	25.77 %	2.21 %

Source: authors' estimates

At a height of 100 m, the analysis revealed that unsuitable land for wind energy farming remained consistent, covering 7 283.84 km^2, or 58.44 % of the total study area. The area deemed less suitable expanded to 736.21 km^2, representing 5.91 % of the region, indicating a slight increase in potential. Moderately suitable land accounted for 3 557.09 km^2, or 28.54 %, suggesting a favorable distribution for wind energy exploitation at this height. However, highly suitable land decreased to 886.61 km^2, which made up 7.11 % of the total area, reflecting a notable reduction in the highest potential areas at this altitude.

At 50 m, the unsuitable land area remained unchanged at 7 283.84 km^2 (58.44 %). However, the less suitable land expanded significantly to 1 692.87 km^2, accounting for 13.58 % of the total area. Moderately suitable land covered 3 211.42 km^2, representing 25.77 %, while the highly suitable area decreased sharply to 275.61 km^2, equaling only 2.21 % of the total area. These findings demonstrate that as the height decreases, the extent of highly suitable land diminishes, while less and moderately suitable areas increase. This pattern highlights the critical influence of elevation on the suitability of regions for wind energy farming, underscoring the importance of higher altitudes in maximizing the potential for wind energy generation in the study area. The shift in suitability across different heights provides crucial insights for selecting optimal locations for wind turbines, with higher elevations showing significantly greater promise.

The analysis reveals that moderately suitable and suitable areas for wind energy farming were consistently found across all assessed heights. Specifically, at 100 m, 28.54 % of the study area was classified as moderately suitable, highlighting this altitude as a favorable zone for wind energy development. However, a notable trend emerged, as the proportion of highly suitable areas decreased progressively with the reduction in height. The highest suitability was observed at 200 m, where the optimal conditions for wind turbines were identified, while at 50 m the highly suitable area reached its lowest extent. Wind speed emerged as the most critical factor influencing the establishment of wind turbines, as it directly affects energy generation. In the case of the middle Zarafshan valley, the data indicates strong wind speeds exceeding 7 m/s at elevations above 100 m, making it a prime location for wind energy exploitation. Areas with such strong winds are deemed particularly advantageous for harnessing wind energy, reinforcing the valley's potential as a wind energy zone. The study produced raster layers illustrating wind potential across various heights, generated through the weighted overlay model. These layers, displayed in Fig. 6a–d, clearly identify the spatial distribution of wind energy potential. The most suitable lands for wind turbine installation were found along the northern and southern boundaries of the middle Zarafshan valley. These regions, with their high wind speeds and favorable topographic conditions, present excellent opportunities for developing wind energy infrastructure, providing a strong case for strategic investment in renewable energy initiatives in this area. The study underscores the necessity of height consideration in maximizing wind energy potential, with the most productive zones lying at higher altitudes.

The results of the current study suggest that the land suitability for wind power farms is highly variable and dependent on different heights within the regions of the middle Zarafshan River valley. The present study has been conducted on a macro level, providing a broad-scale analysis applicable across various regions. The model developed in this research offers a versatile framework that can be adapted to other geographic areas globally. By utilizing this model, it is possible to identify and evaluate regions with the highest potential for wind energy farming. This methodology can serve as a valuable tool for decision-makers and stakeholders looking to optimize site selection for wind energy projects, ensuring a more efficient and sustainable approach to harnessing renewable energy in diverse environmental and climatic contexts. In terms of governance, national policies and priorities have to reduce the usage of fossil fuels by replacing them with clean and sustainable energy alternatives. This study offers valuable insights into the development and utilization of renewable energy resources as a sustainable alternative to conventional energy sources. It is recommended that the government of the Republic of Uzbekistan implement strategic measures to transform the region into a wind energy zone, aligning with the objectives of the UN Sustainable Development Goals. Additionally, such policies will contribute significantly to meeting climate targets. The model presented in this research holds great potential for policymakers, providing crucial data to assess the region's capacity for renewable energy production, thereby supporting long-term energy sustainability and environmental resilience.

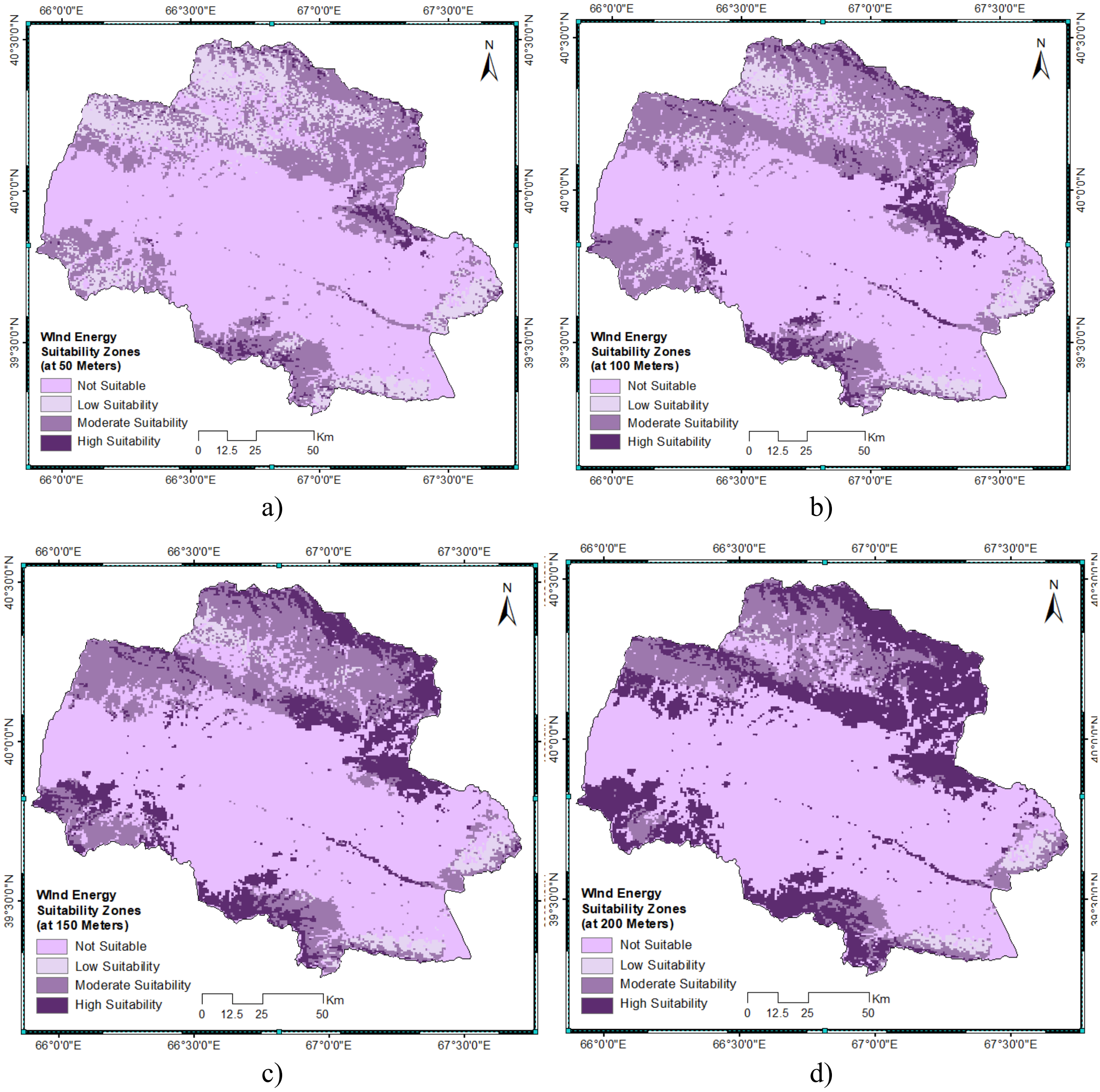


Fig. 6. Zoning of land suitability of wind energy farming in the study area (a–d)

CONCLUSIONS

The present study was undertaken to evaluate the effectiveness of geospatial datasets combined with weighted overlay models in forecasting wind power generation potential in the middle Zarafshan Valley. A comprehensive suitability index was calculated by incorporating multiple factors, including wind speed, terrain slope, proximity to road networks, distance to power transmission lines, and land use/land cover patterns. The findings revealed that the northern and southern parts of the valley emerged as the most suitable areas for wind power exploitation. These regions are characterized by undisturbed landscapes, low population density, well-connected road infrastructure, and other favorable conditions, making them ideal for renewable energy development. Among the four height categories examined, the lower elevations of 50 and 100 m showed the highest potential for wind energy generation compared to the higher elevations of 150 and 200 m. At 50 and 100 m, highly suitable and moderately suitable areas accounted for approximately 28 % and 36 % of the total land, respectively. This suggests that lower heights are more likely to generate greater wind energy due to sustained wind intensities at those elevations. Additionally, the selected region includes Samarkand, Uzbekistan's second-largest city, indicating that economic viability and energy demand may further enhance the region's potential for wind energy development. The proximity to an urban center like Samarkand could play a critical role in energy generation and consumption, thereby contributing to energy conservation and the mitigation of climate change impacts. The study's results underscore the importance of selecting regions with optimal height and wind intensity for maximizing the benefits of wind power, offering a sustainable energy solution for Uzbekistan.

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