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Wind energy potential mapping in Karnataka, India, using GIS

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Abstract

Increasing negative effects of fossil fuel combustion on the environment in addition to limited stock have forced many countries to explore and change to environmentally friendly alternatives that are renewable to sustain the increasing energy demand. Changing to renewable sources and implementation of effective conservation measures would ensure sustainability. Currently, wind energy is one of the fastest developing renewable energy source technologies across the globe. Wind energy is an alternative clean energy source compared to fossil fuel, which pollute the lower layer of the atmosphere. It has the advantage of being harnessed on a local basis for application in rural and remote areas. In order to tap the potential of wind energy sources, there is a need to assess the availability of the resources spatially. Mapping potential sites for tapping wind energy in Karnataka (a federal State in India) is the focus of this study. The study employs the geographical information system (GIS) to map the wind energy resources of Karnataka state and analyse their variability considering spatial and seasonal aspects. Considering these, the present status of the potential is assessed and maps of locations suitable for tapping wind energy have been prepared. A spatial data base with data of wind velocities has been developed and used for evaluation of the theoretical potential through continuous monitoring and mapping of the wind resources. The study shows that the average

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wind velocity in Karnataka varies from 0.85 m/s in Bagalkote to 8.28 m/s in Chikkodi during the monsoon season. Chikkodi, in Belgaum district, has high wind velocity during the period May to September with a peak value of 9.18 m/s in July. Agroclimatic zone wise analysis shows that the northern dry zone and the central dry zone are ideally suited for harvesting wind energy for regional economic development.

Keywords: Wind velocity; Wind energy potential; GIS; Agroclimatic zones

1. Introduction

Wind energy is ultimately a solar resource. Large scale wind systems are created mainly because of temperature differences between the earth's latitudes and deflection caused by the earth's rotation. Dry air in the vicinity of 30° N and 30° S sinks and flows towards the equator, where it replaces rising hot air (often referred to as Hadley circulation). At mid latitudes, between 30° and 70° north and south, air flows towards the pole and is deflected westwards [1]. Wind speed, air density, latitudes, surface roughness, terrain, atmospheric pressure, average temperature, land use pattern etc. will significantly influence wind velocity.

The kinetic energy of the wind is a promising source of renewable energy with significant potential in many parts of the world. The total annual kinetic energy of air movement in the atmosphere is estimated to be around 3×10^{15} kWh or about 0.2% of the solar energy reaching the earth. The maximum technically usable potential is estimated theoretically to be 30×10^{12} kWh/year or about 35% of the current world total energy consumption [2]. Windmills are used to harness wind energy. The power of wind blowing at 25.6 km/h is about 200 W/m^2 of the area swept by a windmill. Approximately 36% of this power can be captured by the windmill and converted to electricity [3].

The power P due to the kinetic energy of the wind is proportional to 1/2 (mass × velocity^2), i.e. the mass of air passing through an area A in a unit time (ρAv) with a velocity v. The total power available from wind is given by Eq. (1).

$$P = [1/2(\rho A v)v^2] = [1/2\rho A v^3] \tag{1}$$

where ρ is mass density, ρAv is air mass flow rate and v is air stream velocity.

The annual average wind speed at a location is useful as an initial indicator of the value of the wind resource. A level of 10 m is the standard height for a typical meteorological station to measure wind speed. If the data collected is at a different height, they are adjusted to 10 m by the India Meteorological Department according to Eq. (2),

$$v = v_o[h/h_o]^k \tag{2}$$

where v is wind speed at height h (m/s), v_o is wind speed at the anemometer height h_o (m/s), h is height at which wind speed is measured (m), h_o is anemometer height (10 m) and k is the height exponent (0.14–0.3).

Modern wind turbines have hub heights greater than 10 m, hence wind speed is extrapolated to a 30 m or 50 m level in order to provide a common basis to compare two sites for which the wind speed has been measured at different heights. The relationship between the annual mean wind speed and the potential value of the wind energy resource is listed in Table 1 [5].

Table 1
Annual mean wind speed and potential value of the wind energy resource

Annual mean wind speed at 10 m Ht	Indicated value of wind resource
< 4.5 m/s	Poor
4.5–5.4 m/s	Marginal
5.4 – 6.7 m/s	Good to very good
> 6.7 m/s	Excellent (or exceptional)

The wind power density P, or the power per unit area normal to the wind, is expressed in W/m^2. The wind power density of a stream of air with mass density ρ moving with a velocity v is given by,

$$P = K_{Em}\rho v^3/2 \tag{3}$$

where K_{Em} is the energy pattern factor. It is employed for stations where hourly wind speed data is not available.

$$K_{Em} = (\Sigma v_i^3/N_m)/v_m^3 \tag{4}$$

where v_i is hourly wind speed during the month, N_m is number of hourly wind speed values during the month and v_m is monthly mean wind speed. For a Rayleigh distribution of wind speed, $K_{Em} = 1.91$.

The energy that can be captured by wind mills is highly dependent on the local average wind speed. Regions that normally present the most attractive potential are located near coasts, inland areas with open terrain or on the edge of water bodies. In spite of these geographic limitations for wind energy project settings, there is an ample terrain in most areas of the world to meet a significant portion of the local electricity needs with wind energy [4].

2. Literature review

Khan et al. [6] have generated a wind energy map of Bangladesh, which incorporates several microscale features, such as terrain roughness, elevation etc. with a mesoscale model. Several meso-maps were obtained from global data bases, and a suitable model was chosen and modified for a 30 m elevation. It was found that the generated wind map and the modified ground data were similar. The annual average wind speed at 30 m height along the coastal belt is above 5 m/s. The wind speed in northeastern parts is above 4.5 m/s, while the inland wind speed is around 3.5 m/s for most parts of Bangladesh.

Tarawneh et al. [7] have estimated the average wind speed in some parts of Jordan using a standard regional dependence function (SRDF) based on the concept of the point cumulative semivariogram (PCSV). At the Azark station, the measured wind speed was 2.54 m/s, the estimated wind speed was 2.44 m/s and the percent error was 3%. This method gives reliable results in estimating the wind speed in Jordan during most months in a year, except in summer. The method can also be used in determining the borders between different wind regimes. The PCSV and SRDF graphs explain the transition zones between the climatic regions of Jordan.

Celik [8] has estimated monthly wind energy production using Weibull representative wind data for a total of 96 months from five different locations in the world (Cardiff, Canberra, Davos, Athens, Ankara). The Weibull parameters were determined based on wind distribution statistics, calculated from measured data, using the gamma function. The wind data in relative frequency format was obtained from these calculated Weibull parameters. The wind speed data in time series format and the Weibull representative wind speed data were used to calculate the wind energy output of a specific wind turbine. Most of the monthly mean wind speeds are between 2.0 and 3.0 m/s, some over 3.0 m/s and a few over 4.0 m/s and under 2.0 m/s.

Chang et al. [9] have analysed the wind characteristics and wind turbine characteristics in Taiwan, based on a long term measured data source (1961–1999) of hourly mean wind speed at 25 meteorological stations across Taiwan. The results show the general availability of the wind energy potential across Taiwan. The monthly wind speed distributions, the monthly wind power densities, the wind energy generated by an ideal turbine and the actual wind energy generated by a wind turbine were estimated as 7.19 m/s, 429.42 W/sq.m, 4.89 kWh, 1.64 kWh respectively for the month of January.

Using information from a questionnaire and available published literature, Geographical Information System (GIS) assisted wind farm location criteria were developed by Baban et al. [10] for the UK. A GIS (IDRISI) was employed to apply these criteria using two different methods to combine information layers for a site in Lancashire. The weights for each layer were allocated based on a pair-wise comparison of the relative importance of the two layers by rating rows relative to columns and entering the ratings into a matrix. The procedure then requires that the principle eigenvector of the pair-wise matrix be computed to produce a best fit set of weights. This approach was used to develop a pair-wise matrix for all the layers. The WEIGHT module, which computes a best fit set of weights for a reciprocal pair-wise matrix in IDRISI, was used to calculate the principle eigenvector directly. This information was used to determine suitability based on the weighted layers. The analysis in terms of areas occupied by each suitability class shows that the most suitable areas occupy 8.32% of the total study area while the least suitable sites cover 70.26% of the area.

Aras [11] has assessed the wind energy status of Turkey. Wind speeds are higher in Bandlrma 5.1–5.2 m/s, 6.3–7 m/s in Bozcaada, 6.4 m/s in Karaburun and Karabiga, 7.1 m/s in Nurdağl and 7 m/s in Senköy. While the average density of wind power is below 40 W/m^2 in 89.3% of Turkey's total domain, it is over 40 W/m^2 in 10.7%, and it exceeds 100 W/m^2 in 0.8%. In spite of the fact that the technical potential of Turkey's wind energy is approximately 88,000 MW, its total established power is only 18.9 MW. The aim is to meet 3.55% of the total energy required via wind by the year 2025.

Hillring et al. [12] have calculated wind energy using a modeling tool such as WA^{s}P, which is a program for extrapolating wind data in horizontal and vertical directions using ground surface data on topography and land use. Time series of recorded wind data were analysed using the raw data analysis option in WA^{s}P. Analysis of the data and presentation of the results from the model studies are analysed with the Arc View geographic information system. The wind energy potential at 50 m level is 8.6 GJ/m^2/year. Theoretically, the 375 km^2 area, with annual wind energy potential >8.6 GJ/m^2 wind energy may produce an annual gross energy of 360–3200 TJ with available technology.

Cheng et al. [13] have proposed a model to estimate wind speed for regional analysis. A Rayleigh Simulation Model (RSM) is developed to use the available short term and fragmentary wind data. The RSM is basically a process of generating extreme winds by means of estimating the tail quantile probability from historical data. The RSM is applied to 21 stations in Texas where wind data are of short period and in wind rose format. The results obtained from the application of the proposed RSM were encouraging. From this, a dimensionless regional frequency curve was constructed, which could serve as an effective means of estimating wind speeds for prescribed recurrence at ungauged sites.

3. Objective

The main objectives of the study are to:

- Assess the availability of wind energy resources in Karnataka based on season wise and location wise data of wind velocity,
- Spatially map wind energy sources and
- Analyse wind potential according to agro-climatic zones.

4. Study area

The study was conducted for Karnataka State, India, based on data compiled from various sources for various locations. The State of Karnataka is confined roughly within 11°31′ North and 18°45′ North latitudes and 74°12′ East and 78°40′ East longitude and lies in the western central part of peninsular India (Fig. 1). It is situated on a tableland where the Western and Eastern Ghat ranges converge into the Nilgiri hill complex. Karnataka's total land area is 191,791 sq. km. There are 27 districts with 175 taluks in Karnataka.

Physiograpically, Karnataka State forms part of three well defined macro regions of the Indian Union; the Deccan Plateau, the hilly region and the Coastal plains and islands. The State has four physiographic regions.

- Northern Karnataka Plateau
- Central Karnataka Plateau
- Southern Karnataka Plateau
- Karnataka Coastal Region

Topographically Karnataka has representatives of all types of variations in topography, high mountains, plateaus, residual hills and coastal plains. Chains of mountains to its west, east and south enclose the State. It consists mainly of plateau, which has a higher elevation of 600–900 m above mean sea level. The entire landscape is undulating, broken by mountains and deep ravines. Plain land of elevation less than 300 m above mean sea level is to be found only in the narrow coastal belt, facing the Arabian Sea. There are quite a few high peaks, both in the Western

Fig. 1. Study area.

and Eastern Ghat systems, with altitudes more than 1,500 m. A series of cross sections drawn from west to east across the Western Ghat generally exhibit a narrow coastal plain followed to the east by small and short plateaus at different altitudes and then suddenly rising to great heights.

5. Methodology

The ideal way to predict the wind potential of a region is to acquire long term records of wind speed from a large number of well exposed stations all over the region. Wind energy potential for various locations in Karnataka is calculated based on wind data (annual average wind speed). There are 29 IMD (India Meteorological Department) surface observatories in Karnataka. Annual average wind velocity data for these 29 wind monitoring stations were collected from the IMD, Govt. of India, Pune. Table 2 lists the location wise duration of data available.

A detailed analysis was done for potentially good stations such as Chikkodi, Horti, Kahanderayanahalli, Kamkarhatti, Raichur and Bidar to analyse variations across various months. To account for variations across seasons, the data was grouped season wise as summer (February–May), monsoon (June–September) and winter (October–January). Season wise mean wind velocity and standard deviation were computed for the 29 wind monitoring stations.

Table 2
Duration of wind data (location/station wise)

Station name	Station index	Years of data
Bagalkote	16205	12 (1984–1996)
Gulbarga	43121	95 (1901–1996)
Bidar	43125	95 (1901–1996)
Bijapur	43161	95 (1901–1996)
Raichur	43169	95 (1901–1996)
Gadag	43201	64 (1932–1996)
Bellary	43205	95 (1901–1996)
Karwar	43225	95 (1901–1996)
Honnavar	43226	57 (1939–1996)
Shirali	43229	20 (1976–1996)
Chitradurga	43233	95 (1901–1996)
Thirthahalli	43257	45 (1951–1996)
Shimoga	43258	44 (1952–1996)
Sringeri	43259	63 (1933–1996)
Chikmagalur	43260	22 (1974–1996)
Hassan	43263	95 (1901–1996)
Tumkur	43268	24 (1972–1996)
Mangalore	43284	40 (1956–1996)
Mercara	43287	95 (1901–1996)
Mandya	43289	24 (1972–1996)
Mysore	43291	95 (1901–1996)
Bangalore	43296	47 (1949–1996)
Bangalore	43295	47 (1949–1996)
Bangarpet	43299	24 (1972–1996)
Chikkodi (Belgaum)	431972	4 (1993–1997)
Horti	431973	4 (1993–1997)
Kamkarhatti	431974	4 (1993–1997)
Kahanderayanahalli	432013	4 (1993–1997)

A Geographic information system (GIS) is used for mapping wind resources spatially and to quantify and analyse temporal changes. Based on these, GIS thematic layers were generated, which help in assessing the variability. The map helps to identify the most and the least suitable potential areas for harnessing wind energy.

Assessment in different agro-climatic zones is based on compilation and computation of monthly mean wind speed of wind energy for the 29 wind monitoring stations located in the various agro-climatic zones. Karnataka is divided into 10 agro-climatic zones taking into consideration the rainfall pattern, quantum and distribution, elevation, topography, soil types, texture, depth and physio-chemical properties, major crops and type of vegetation. The agro-climatic zones (Fig. 2) considered are:

- Northern dry zone
- Central dry zone
- Northern transition zone
- Eastern dry zone
- Northeastern transition zone

Fig. 2. Agro-climatic zones in Karnataka.

- Southern dry zone
- Coastal zone
- Hilly zone
- Northeastern dry zone
- Southern transition zone

6. Wind data presentation, discussion and analysis

The data, collected under the Wind Resources Assessment Programme (WRAP) of Karnataka, indicate that the wind energy potential is of the order of 7161 MW and commercial exploitation is about 864 MW. As of date, 1169 MW of wind capacity has been allocated to 89 developers in the State and 24 projects with an installed capacity of 79 MW have been commissioned. The gross potential of wind energy in Karnataka is 6620 MW (assuming 1% land availability for wind farms) [14].

Apart from IMD stations, Karnataka has 52 well established wind monitoring stations maintained and managed by Karnataka Renewable Energy Development Limited (KREDL). Among the KREDL wind monitoring stations, 33 stations were established by the Ministry of Non-conventional Energy Sources (MNES), Government of India, and 19 by the Karnataka Power Corporation Ltd. (KPCL). Seventeen of the MNES stations and 9 KPCL stations are established in places where the annual average wind power density is greater than 150 W/m^2.

7. Results

7.1. Season wise, location wise availability of wind energy

The monthly mean wind velocity data were analysed location wise and season wise based on the historical monthly data as discussed in methodology to assess the variability across locations and seasons. The mean wind velocity and standard deviation computed for each location month wise and for various seasons are listed in Tables 3–5, respectively. It is noted that the average wind velocities in Karnataka vary from 0.53 ± 0.1 m/s (in Bagalkote) to 6.06 ± 0.4 m/s (at Chikkodi, Belgaum) during summer, 0.85 ± 0.2 m/s (in Bagalkote) to 8.28 ± 0.5 m/s (at Chikkodi, Belgaum) during monsoon and 0.34 ± 0.1 m/s (in Bagalkote) to 5.19 ± 1.0 m/s (at Chikkodi, Belgaum) during winter.

Locations with annual mean wind velocity greater than 5.4 m/s are considered ideal for harvesting wind energy. Fig. 3 is a pictorial representation of the month wise variation of the wind

Table 3
Variation of wind velocity in m/s during summer at different stations

Station name	Station index	Wind velocity during summer (mean ± standard deviation)				Average
		February	March	April	May	
Bagalkote	16205	0.35 ± 0.11	0.42 ± 0	0.48 ± 0.03	0.86 ± 0.26	0.53 ± 0.1
Gulbarga	43121	2.45 ± 0.68	2.61 ± 0.68	2.92 ± 0.71	3.73 ± 0.92	2.93 ± 0.7
Bidar	43125	2.78 ± 0.61	2.81 ± 0.51	2.91 ± 0. 48	3.53 ± 0.59	3.01 ± 0.6
Bijapur	43161	1.53 ± 0.44	1.72 ± 0.48	2.05 ± 0.58	2.97 ± 0.83	2.07 ± 0.6
Raichur	43169	2.65 ± 0.52	2.75 ± 0.48	2.90 ± 0.55	3.87 ± 0.89	3.05 ± 0.6
Gadag	43201	1.99 ± 0.53	2.26 ± 0.43	2.79 ± 0.33	3.78 ± 0.59	2.71 ± 0.5
Bellary	43205	1.44 ± 0.43	1.57 ± 0.39	1.81 ± 0.38	2.70 ± 0.66	1.89 ± 0.5
Karwar	43225	1.57 ± 0.57	1.82 ± 0.66	2.17 ± 0.75	2.49 ± 1.0	2.02 ± 0.7
Honnavar	43226	1.63 ± 0.54	1.64 ± 0.53	1.70 ± 0.54	1.94 ± 0.64	1.73 ± 0.6
Shirali	43229	1.85 ± 0.21	1.81 ± 0.41	1.93 ± 0.32	2.15 ± 0.41	1.94 ± 0.3
Chitradurga	43233	2.02 ± 0.53	2.05 ± 0.55	2.20 ± 0.56	3.10 ± 0.72	2.35 ± 0.6
Thirthahalli	43257	0.97 ± 0.28	0.90 ± 0.31	1.13 ± 0.34	1.26 ± 0.51	1.07 ± 0.4
Shimoga	43258	1.01 ± 0.31	1.10 ± 0.34	1.18 ± 0.39	1.50 ± 0.42	1.2 ± 0.4
Sringeri	43259	1.25 ± 0.29	1.23 ± 0.47	1.07 ± 0.35	1.05 ± 0.24	1.15 ± 0.3
Chikmagalur	43260	1.30 ± 0.33	1.42 ± 0.32	1.52 ± 0.37	1.99 ± 0.52	1.56 ± 0.4
Hassan	43263	1.50 ± 0.36	1.69 ± 0.35	2.06 ± 0.54	2.77 ± 0.74	2.01 ± 0.5
Tumkur	43268	2.10 ± 0.30	1.96 ± 0.64	1.62 ± 0.58	1.69 ± 0.58	1.85 ± 0.5
Mangalore	43284	1.58 ± 0.32	1.60 ± 0.32	1.84 ± 0.68	1.87 ± 0.46	1.73 ± 0.5
Mercara	43287	1.96 ± 0.63	1.84 ± 0.54	1.87 ± 0.54	2.32 ± 0.71	2 ± 0.6
Mandya	43289	0.94 ± 0.35	0.94 ± 0.21	1.19 ± 0.18	1.19 ± 0.33	1. 07 ± 0.3
Mysore	43291	2.46 ± 0.80	2.31 ± 0.65	2.29 ± 0.66	2.79 ± 0.66	2.47 ± 0.7
Bangalore	43296	1.81 ± 0.55	1.92 ± 0.47	1.83 ± 0.42	2.93 ± 0.92	2.22 ± 0.7
Bangalore	43297	1.91 ± 0.65	1.99 ± 0.55	2.03 ± 0.48	2.93 ± 0.92	2.22 ± 0.7
Bangarpate	43299	1.83 ± 0.23	1.80 ± 0.16	1.74 ± 0.17	2.19 ± 0.37	1.89 ± 0.2
Chikkodi (Belgaum)	431972	4.93 ± 0.48	5.32 ± 0.30	6.03 ± 0.50	7.96 ± 0.36	6.06 ± 0.4
Horti	431973	4.36 ± 0.42	4.50 ± 0.06	4.54 ± 0.18	5.87 ± 0.48	4.82 ± 0.3
Kamkarhatti	431974	4.77 ± 0.12	4.73 ± 0.051	5.22 ± 0.19	6.19 ± 0.23	5.23 ± 0.1
Kahanderayanahalli	432013	4.15 ± 0.50	4.39 ± 0.32	4.36 ± 0.35	6.16 ± 0.25	4.77 ± 0.4

Table 4
Variation of wind velocity in m/s during monsoon at different stations

Station name	Station index	Wind velocity during monsoon (mean ± standard deviation)				Average
		June	July	August	September	
Bagalkote	16205	1.00 ± 0.23	1.11 ± 0.23	0.84 ± 0.08	0.45 ± 0.11	0.85 ± 0.2
Gulbarga	43121	4.80 ± 0.99	4.92 ± 1.24	4.39 ± 0.96	3.12 ± 0.87	4.31 ± 1.0
Bidar	43125	5.30 ± 1.15	5.30 ± 1.45	4.58 ± 1.12	3.22 ± 0.79	4.61 ± 1.1
Bijapur	43161	3.88 ± 0.83	4.23 ± 1.13	3.94 ± 0.93	2.72 ± 0.77	3.7 ± 0.9
Raichur	43169	5.10 ± 1.31	5.32 ± 1.54	4.70 ± 1.24	3.52 ± 0.91	4.67 ± 1.3
Gadag	43201	4.97 ± 0.85	5.25 ± 0.88	4.80 ± 0.67	3.66 ± 0.53	4.68 ± 0.7
Bellary	43205	3.68 ± 0.66	3.91 ± 0.70	3.66 ± 0.72	2.88 ± 0.71	3.54 ± 0.7
Karwar	43225	2.57 ± 0.99	3.04 ± 1.40	2.30 ± 1.19	1.48 ± 0.77	2.36 ± 1.1
Honnavar	43226	2.03 ± 0.73	2.07 ± 0.91	1.82 ± 0.75	1.34 ± 0.53	1.82 ± 0.7
Shirali	43229	2.28 ± 0.46	2.25 ± 0.52	2.00 ± 0.35	1.51 ± 0.18	2.01 ± 0.4
Chitradurga	43233	4.08 ± 0.82	4.19 ± 0.79	3.86 ± 0.79	3.07 ± 0.79	3.8 ± 0.8
Thirthahalli	43257	1.76 ± 0.55	2.03 ± 0.67	1.65 ± 0.60	1.06 ± 0.41	1.63 ± 0.6
Shimoga	43258	1.75 ± 0.37	1.62 ± 0.35	1.35 ± 0.39	1.19 ± 0.33	1.48 ± 0.4
Sringeri	43259	1.24 ± 0.28	1.64 ± 0.50	1.24 ± 0.38	1.07 ± 0.26	1.3 ± 0.4
Chikmagalur	43260	3.03 ± 0.84	3.10 ± 0.78	2.94 ± 0.87	2.09 ± 0.60	2.81 ± 0.8
Hassan	43263	3.58 ± 0.85	3.63 ± 0.91	3.22 ± 0.82	2.76 ± 0.70	3.3 ± 0.8
Tumkur	43268	2.33 ± 1.10	2.11 ± 1.02	1.88 ± 0.80	1.80 ± 0.49	2.03 ± 0.9
Mangalore	43284	1.92 ± 0.36	1.96 ± 0.51	1.75 ± 0.46	1.46 ± 0.33	1.78 ± 0.4
Mercara	43287	3.07 ± 0.83	3.90 ± 1.01	3.60 ± 0.91	2.76 ± 0.84	3.34 ± 0.9
Mandya	43289	1.37 ± 0.41	1.93 ± 0.41	1.80 ± 0.53	1.39 ± 0.33	1.63 ± 0.4
Mysore	43291	3.98 ± 0.89	4.01 ± 0.91	3.56 ± 0.76	2.90 ± 0.77	3.62 ± 0.8
Bangalore	43296	5.06 ± 1.32	5.01 ± 1.42	4.41 ± 1.17	2.95 ± 0.89	4.36 ± 1.2
Bangalore	43297	5.06 ± 1.32	5.00 ± 1.42	4.41 ± 1.17	2.95 ± 0.89	4.36 ± 1.2
Bangarpate	43299	3.21 ± 0.42	3.12 ± 0.46	2.98 ± 0.45	2.19 ± 0.38	2.87 ± 0.4
Chikkodi (Belgaum)	431972	8.29 ± 0.56	9.18 ± 0.58	8.52 ± 0.17	7.10 ± 0.58	8.28 ± 0.5
Horti	431973	8.32 ± 0.78	8.49 ± 0.20	7.79 ± 0.90	5.54 ± 0.98	7.54 ± 0.7
Kamkarhatti	431974	6.72 ± 0.45	7.78 ± 0.792	7.11 ± 0.43	5.95 ± 0.21	6.9 ± 0.5
Kahanderayanahalli	432013	7.56 ± 0.62	7.95 ± 0.65	7.06 ± 0.56	5.61 ± 0.56	7.05 ± 0.6

velocities at good wind potential sites. It is noted that at Chikkodi (in the Belgaum district), the wind velocity is high during the period May to September with a peak value of 9.18 ± 0.58 m/s in July. Similarly, at Horti, Kahanderayanahalli, Kamkarhatti, Raichur and Bidar, the peak values of wind velocity in July are 8.49 ± 0.20, 7.95 ± 0.65, 7.78 ± 0.79, 5.32 ± 1.54 and 5.30 ± 1.45 m/s respectively.

7.2. *Spatial mapping of wind energy sources*

(GIS) is used for identifying and quantifying the effect of local constraints on the wind energy potential. This helped in providing the flexibility to enrich the database with spatial data on which decisions are based. Thematic maps of the wind potential across various seasons were generated using the GIS in considering the temporal and spatial data of seasonal wind velocities. This will help to identify the regions suitable for harvesting wind energy.

Table 5
Variation of wind velocity in m/s during winter at different stations

Station name	Station index	Wind velocity during winter (mean ± standard deviation)				Average
		October	November	December	January	
Bagalkote	16205	0.43 ± 0.17	0.28 ± 0.09	0.32 ± 0.05	0.31 ± 0.10	0.34 ± 0.1
Gulbarga	43121	2.58 ± 0.76	2.72 ± 0.71	2.32 ± 0.69	2.18 ± 0.68	2.46 ± 0.7
Bidar	43125	2.33 ± 0.58	2.40 ± 0.69	2.44 ± 0.61	2.58 ± 0.66	2.44 ± 0.6
Bijapur	43161	1.45 ± 0.44	1.11 ± 0.31	1.06 ± 0.31	1.29 ± 0.34	1.23 ± 0.4
Raichur	43169	2.66 ± 0.60	2.60 ± 0.48	2.54 ± 0.47	2.57 ± 0.50	2.6 ± 0.5
Gadag	43201	2.22 ± 0.54	2.11 ± 0.69	2.19 ± 0.59	2.12 ± 0.50	2.17 ± 0.6
Bellary	43205	1.46 ± 0.44	1.25 ± 0.48	1.19 ± 0.42	1.30 ± 0.37	1.31 ± 0.4
Karwar	43225	1.17 ± 0.51	1.06 ± 0.49	1.15 ± 0.44	1.31 ± 0.48	1.18 ± 0.5
Honnavar	43226	1.34 ± 0.53	1.40 ± 0.47	1.67 ± 0.60	1.60 ± 0.52	1.51 ± 0.5
Shirali	43229	1.49 ± 0.14	1.91 ± 0.31	2.61 ± 0.71	1.96 ± 0.40	2 ± 0.4
Chitradurga	43233	1.88 ± 0.56	1.88 ± 0.61	2.18 ± 0.50	2.22 ± 0.49	2.04 ± 0.5
Thirthahalli	43257	1.01 ± 0.41	1.38 ± 0.41	1.48 ± 0.71	1.14 ± 0.58	1.26 ± 0.5
Shimoga	43258	0.92 ± 0.22	1.08 ± 0.23	1.20 ± 0.23	1.04 ± 0.26	1.06 ± 0.2
Sringeri	43259	0.95 ± 0.41	1.17 ± 0.33	1.35 ± 0.27	1.43 ± 0.42	1.23 ± 0.4
Chikmagalur	43260	1.41 ± 0.49	1.41 ± 0.42	1.41 ± 0.43	1.23 ± 0.31	1.37 ± 0.4
Hassan	43263	1.71 ± 0.42	1.39 ± 0.31	1.48 ± 0.39	1.49 ± 0.40	1.52 ± 0.4
Tumkur	43268	1.35 ± 0.56	1.70 ± 0.51	1.93 ± 0.52	2.02 ± 0.26	1.76 ± 0.5
Mangalore	43284	1.33 ± 0.30	1.30 ± 0.320	1.47 ± 0.31	1.55 ± 0.35	1.42 ± 0.3
Mercara	43287	1.94 ± 0.63	2.32 ± 0.734	2.65 ± 0.77	2.25 ± 0.71	2.3 ± 0.7
Mandya	43289	1.00 ± 0.20	1.00 ± 0.240	1.07 ± 0.25	0.95 ± 0.22	1.01 ± 0.2
Mysore	43291	2.09 ± 0.64	2.48 ± 0.82	3.01 ± 0.73	2.88 ± 0.74	2.62 ± 0.7
Bangalore	43296	1.79 ± 0.59	1.59 ± 0.43	1.74 ± 0.55	1.79 ± 0.60	1.73 ± 0.5
Bangalore	43297	1.79 ± 0.59	1.59 ± 0.43	1.74 ± 0.55	1.79 ± 0.60	1.73 ± 0.5
Bangarpate	43299	1.48 ± 0.30	1.50 ± 0.28	1.72 ± 0.26	1.79 ± 0.150	1.63 ± 0.3
Chikkodi (Belgaum)	431972	4.72 ± 0.75	5.14 ± 1.132	5.92 ± 1.42	4.97 ± 0.48	5.19 ± 1.0
Horti	431973	4.13 ± 0.44	4.13 ± 0.66	4.39 ± 0.20	4.45 ± 0.30	4.28 ± 0.4
Kamkarhatti	431974	4.42 ± 0.58	5.12 ± 0.82	5.46 ± 0.92	4.83 ± 0.40	4.96 ± 0.7
Kahanderayanahalli	432013	4.18 ± 0.41	4.55 ± 0.84	5.45 ± 0.18	4.52 ± 0.34	4.68 ± 0.4

The variability of wind potential across seasons (summer, monsoon and winter) and across districts in Karnataka State, India, is depicted pictorially through thematic layers in Figs. 4–6, respectively. The wind potential is evaluated station wise and is represented by a polygon in the map and is overlaid on Fig. 1 using the GIS (overlay operation). As seen from Figs. 4–6, a polygon corresponds to a district, which is an administrative unit in India to implement developmental programmes at a disaggregated level. The map also shows the number of wind monitoring stations (which is represented by points in a polygon) (Figs. 5 and 6). It is seen that the wind potential is high in Belgaum and there are five wind monitoring stations in Belgaum.

7.3. Analyses of wind potential according to agro-climatic zones

Karnataka is divided into 10 agro-climatic zones taking into consideration the rainfall pattern, quantum and distribution, soil types, texture, depth and physio-chemical properties, elevation, topography, major crops and type of vegetation. Figs. 4–6 illustrate the trend in wind potential

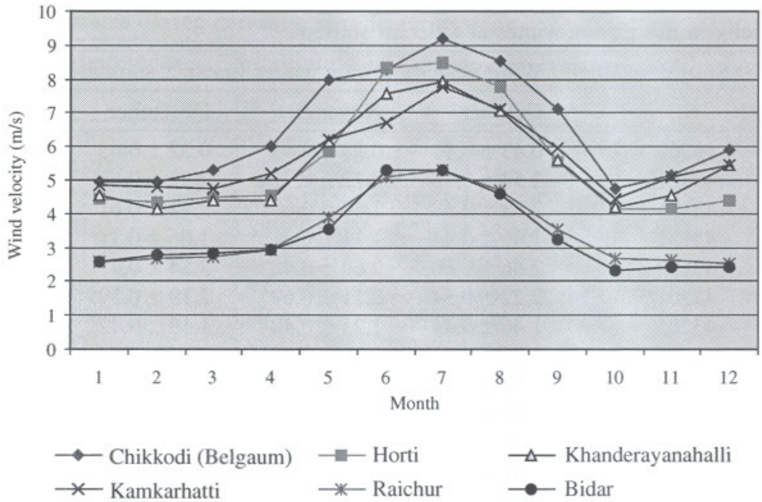

Fig. 3. Monthly variation of wind velocity at high potential sites.

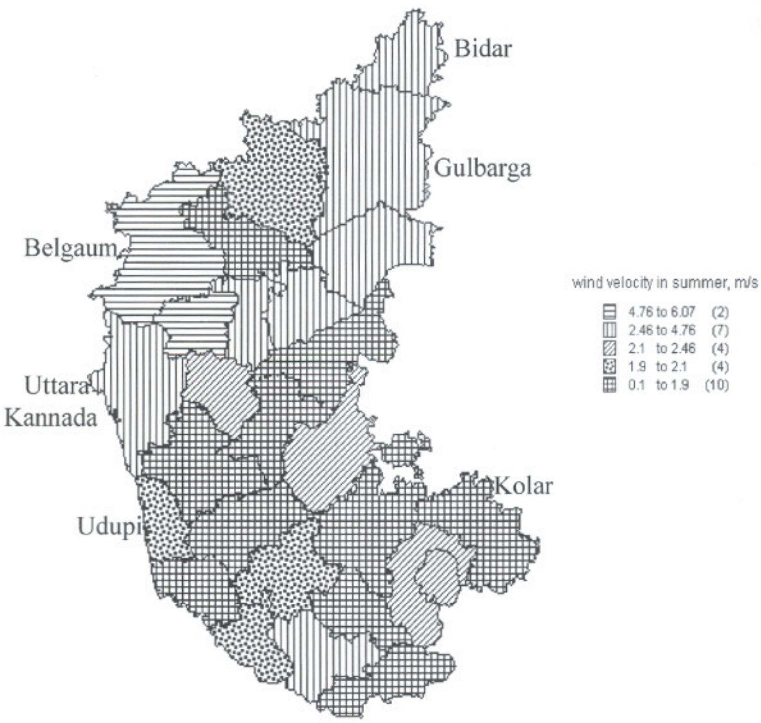

Fig. 4. Station wise variation of wind velocity during summer (m/s).

variation across the various regions that correspond to the agro-climatic zones in Karnataka (Fig. 2). In order to understand the variability within a region, further analysis is done considering each agro-climatic zone separately.

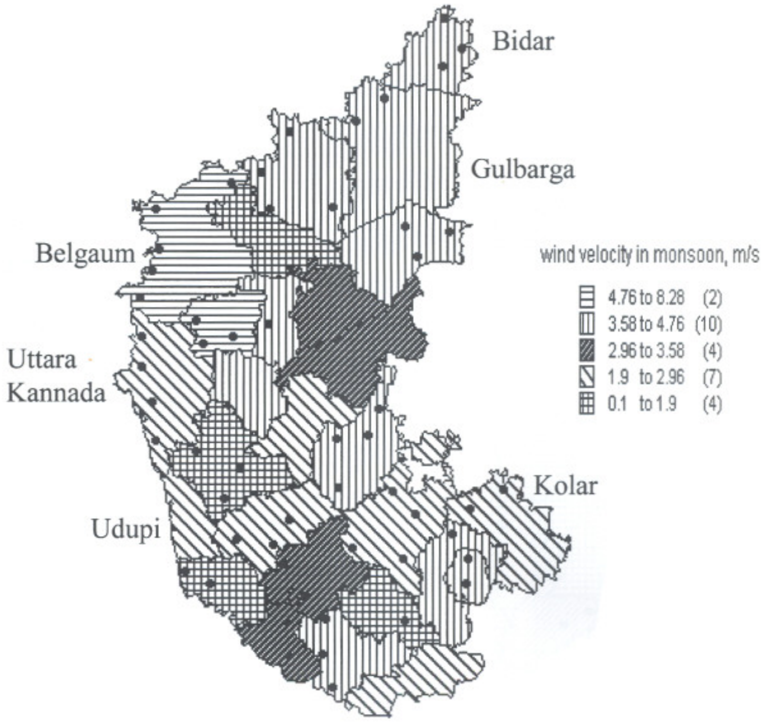

Fig. 5. Station wise variation of wind velocity during monsoon (m/s).

The northern dry zone of Karnataka includes Bijapur, Gadag, Bellary, some parts of Belgaum, Dharwad and Bagalkote districts. Fig. 7 illustrates the variation of wind velocity in the northern dry zone. It shows that Chikkodi in Belgaum has the highest wind velocity of 9.18 ± 0.58 m/s in the month of July and Bagalkote has lowest wind velocity of 0.28 ± 0.09 m/s in the month of November.

The eastern dry zone in Karnataka includes Bangalore, some parts of Kolar and Tumkur districts. Fig. 8 shows that the maximum wind velocity in this zone is found in Bangalore (5.01 ± 1.42 m/s in the month of July) and the minimum wind velocity in Tumkur (1.35 ± 0.56 m/s in the month of October).

The variation of wind velocity in the southern dry zone is shown in Fig. 9, and this zone includes Mysore, Mandya and Hassan districts. It is noticed that Mysore has the maximum wind velocity of 4.01 ± 0.91 m/s in the month of July and the minimum occurs in Mandya with wind velocity of 0.94 ± 0.21 m/s in the month of March.

Fig. 10 illustrates the variation of wind velocity in the hilly zone that includes some parts of the Kodagu and Chikmagalur districts. Mercara in Kodagu has a maximum wind velocity of 3.9 ± 1.01 m/s in the month of July and Sringeri in Chikmagalur has a minimum wind velocity of 0.95 ± 0.41 m/s in the month of October.

The coastal zones in Karnataka include Dakshina Kannada and Uttara Kannada districts. The variation of wind velocity in the coastal zone, as shown in Fig. 11, indicate that Karwar

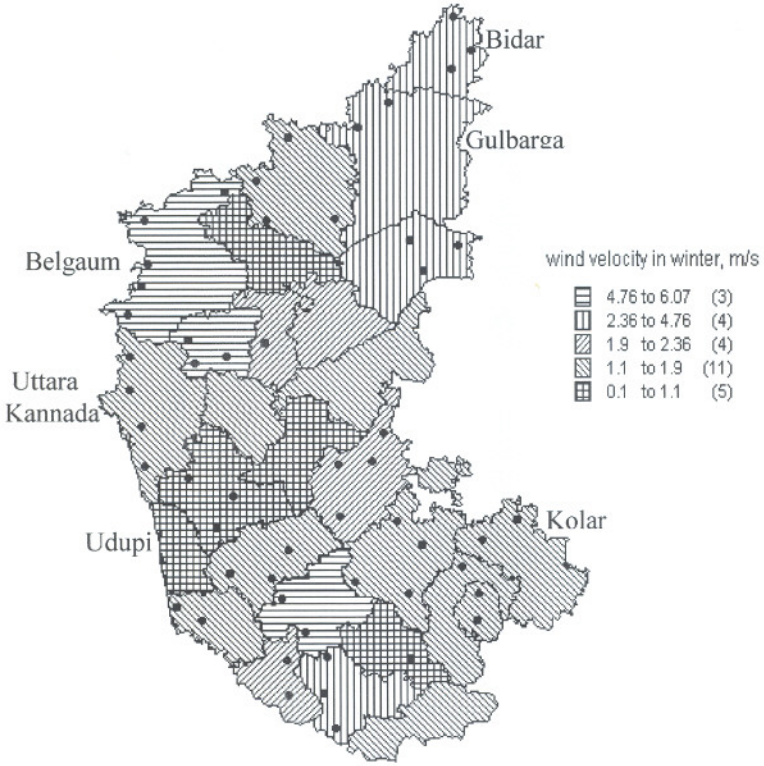

Fig. 6. Station wise variation of wind velocity during winter (m/s).

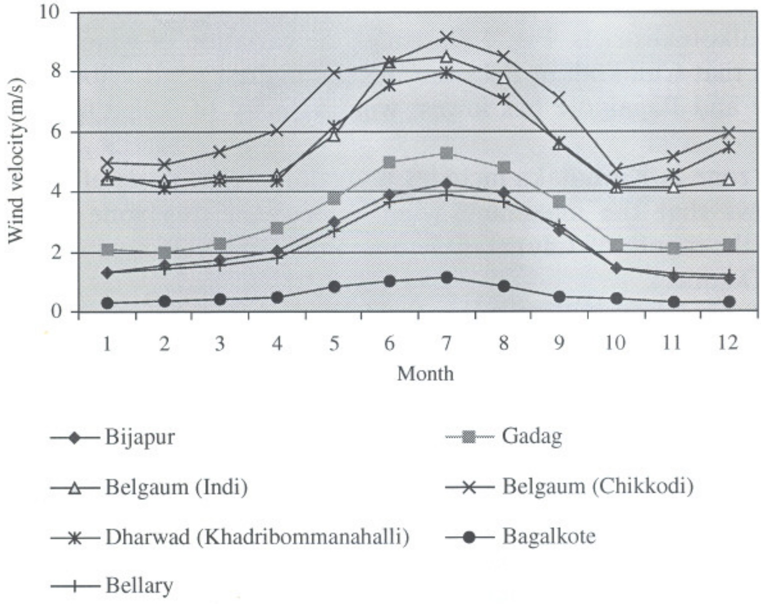

Fig. 7. Monthly variation of wind velocity in northern dry zone.

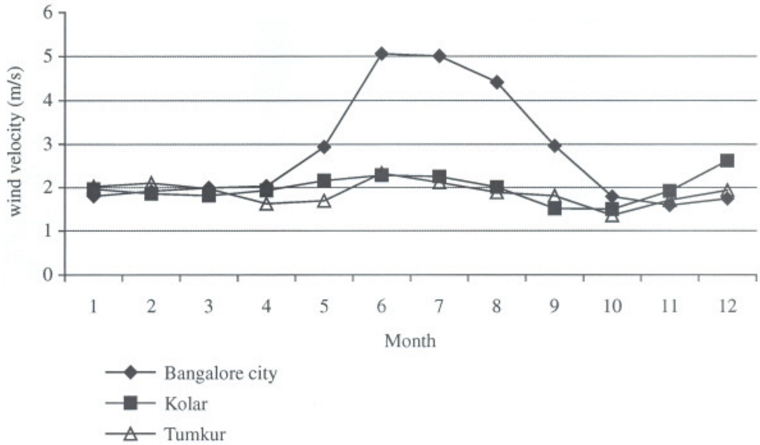

Fig. 8. Monthly variation of wind velocity in eastern dry zones.

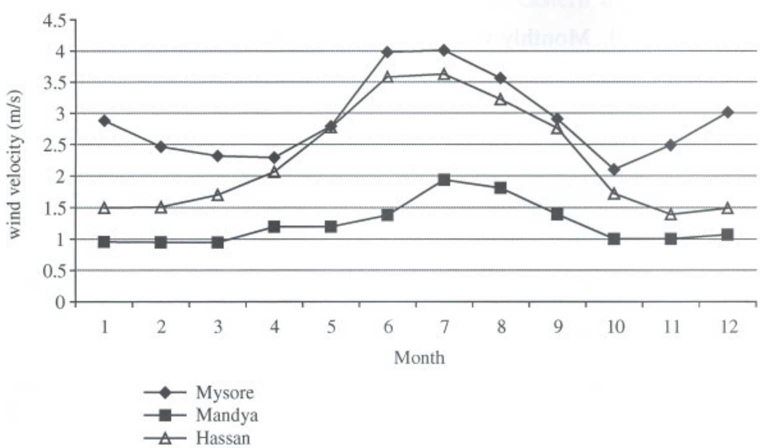

Fig. 9. Monthly variation of wind velocity in southern dry zone.

(in Uttara Kannada) has a maximum wind velocity of 3.04 ± 1.40 m/s in the month of July and a minimum wind velocity of 1.06 ± 0.49 m/s in the month of November.

The central dry zone includes some parts of Chitradurga district, which has a maximum wind velocity of 4.19 ± 0.79 m/s in the month of July and a minimum of 1.88 ± 0.56 m/s in the month of October. Raichur district comes under the northeastern dry zone with a maximum wind velocity of 5.32 ± 1.54 m/s in July and a minimum of 2.54 ± 0.47 in the month of December. Bidar and Gulbarga districts come under the northeastern transition zone. A maximum wind velocity of 5.30 ± 1.45 m/s in the month of July is found in Bidar and a minimum of 2.33 ± 0.58 m/s in the month of October. The variations of wind velocity in these three zones are illustrated in Fig. 12.

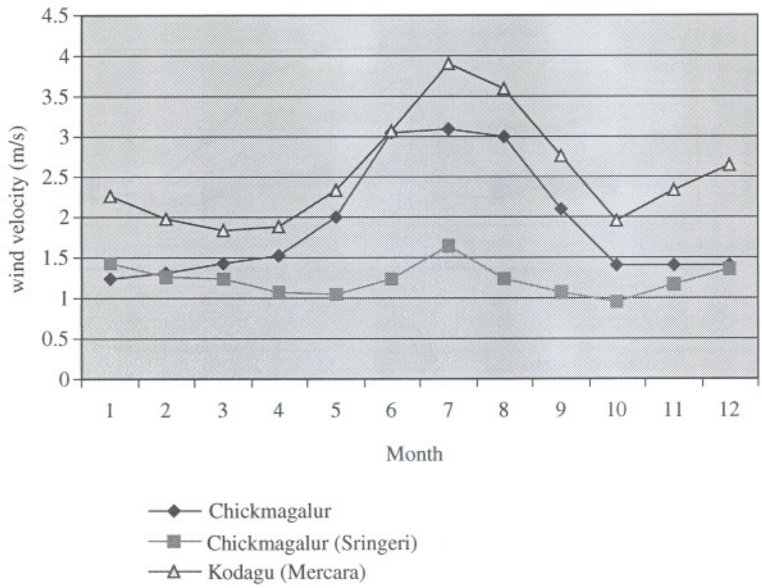

Fig. 10. Monthly variation of wind velocity in hilly zones.

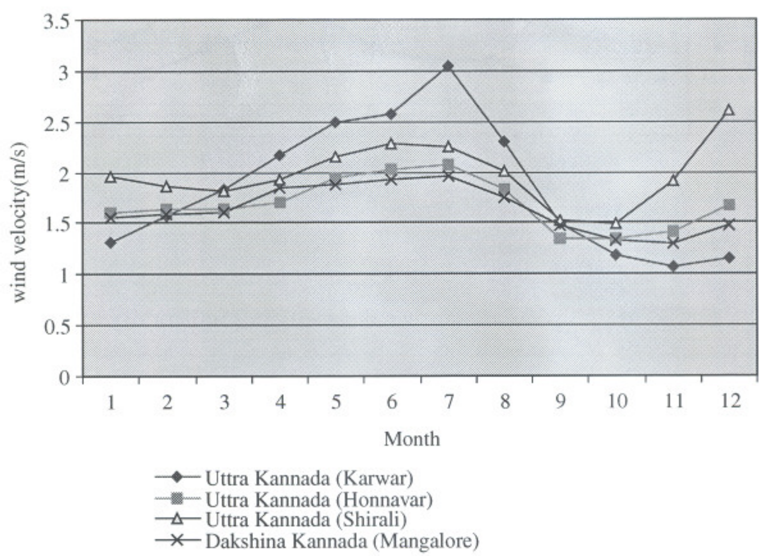

Fig. 11. Monthly variation of wind velocity in coastal zones.

From these discussions, it is evident that the northern dry zone and central dry zone are ideally suited for harvesting wind energy for regional economic development.

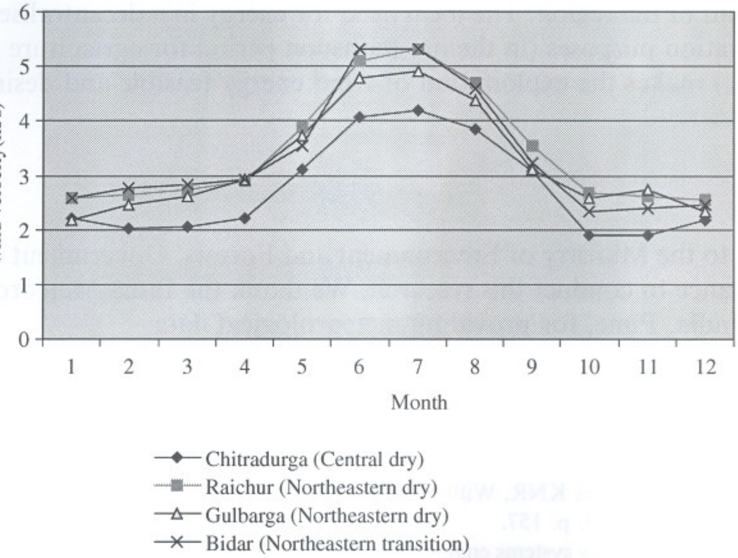

Fig. 12. Monthly variation of wind velocity in central dry zone, northeastern dry zone and northeastern transition zone.

8. Conclusion

An annual mean wind speed less than 5 m/s is not of much relevance to wind energy applications. Chikkodi, Horti, Kahanderayanahalli and Kamkarhatti have wind velocities greater than 5 m/s during most of the months, i.e. the wind energy potential is high in these locations. Hence, these locations are recommended for construction of wind farms.

GIS is potentially well suited for identifying wind energy potential zones as it can manage and analyse the diverse multidisciplinary spatial and temporal data needed in this application. This is useful as a planning tool as it provides the user with the freedom to use their individual expertise in analysing the local conditions and in the decision making process. The wind potential zone maps can be used easily to assist in making appropriate decisions. The GIS also helps in integrating additional relevant layers of information, such as prevailing wind, terrain, adjacent terrain, vegetation, proximity to residential areas, noise and appearance and public satisfaction, which are to be taken into consideration while locating wind farm sites. This also would help in locating the most suitable site among several of the "ideal" sites from the spatial data by assessing their suitability on an individual basis considering various constraints.

The northern dry zone with the highest wind velocity is ideally suited for installing wind farms. Estimates show that if 2% of the wastelands (currently about 30–35% is either barren or uncultivable land in this zone) are used for harnessing wind energy about 0.75–2 MW could be generated at many locations during some seasons. Human pressure on forests to meet the daily energy requirement in the form of fuel wood and fodder for domestic purposes and rural industries is quite evident in drier belts and from the barren hill tops in the coastal districts of Karnataka. Therefore, harnessing a renewable source like wind at feasible sites would help in the eco-development of the region. The local need for energy in a decentralised way for industrial needs and for irrigation purposes (in the pre-monsoon period for agriculture and plantations like areca, coconut etc.) makes the exploitation of wind energy feasible and desirable.

Acknowledgement

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