Basic wind speed map of India with long-term hourly wind data

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Long-term data on hourly wind speed from 70 meteorological centres of India Meteorological Department have been collected. The daily gust wind data have been processed for annual maximum wind speed (in kmph) for each site. Using the Gumbel probability paper approach the extreme value quantiles have been derived. A design basis wind speed for each site for a return period of 50 years has also been evaluated. The site-specific changes in the design wind speeds in the contemporary wind zone map for the design of buildings/structures are highlighted and revision to the map is suggested.

Keywords: Anemograph stations, buildings and structures, return period, wind speed map.

THE wind speed map included in the IS:875 (Part-3)[1], serves the primary purpose of choosing the appropriate basic wind velocity for the design of buildings and structures. The recommended basic wind speed in the map refers to peak gust velocity averaged over 3 s duration, at a height of 10 m above ground level in a Category-2 terrain (open terrain with average obstructions on the surface being small and scattered), with a mean return period of 50 years. It is based[1] on the then available up-to-date wind data till 1982 from 43 anemograph (DPT, Dines Pressure Tube) stations spread over the country, obtained from India Meteorological Department (IMD). The currently used design wind speeds are based on their return period at different locations. At the IMD meteorological stations, wind velocity is in general measured using the DPT installations at varying heights of 10–30 m. These records have been used to carry out an extreme value analysis by several meteorologists[2–5] and by committee members responsible for the formulation of wind speed maps. In an attempt to re-examine the validity of the available basic wind speeds for different regions, the Structural Engineering Research Centre (SERC), Chennai, has undertaken reviewing of the basic wind speeds based on the updated IMD data. However, only 70 out of the total 500 ground observatories of IMD spread out in India have the hourly wind data, including daily gust winds. SERC pro-

cured all the available wind data from these 70 stations[6]. Most of these stations are either airports, seaports or regional meteorological observatories. Isotachs (lines of equal velocity) in the wind speed map seem impossible even now with the updated wind data, which are scanty and not available for longer term at a close enough grid of the meteorological stations. The number of stations where updated data are available from IMD is 3, 25, 9, 15, 17 and 0 respectively, for zones 1 to 6 of IS:875 (Part 3)[1]. The National Data Centre at IMD, Pune, which is the authorized clearing agency for the meteorological data, has supplied all the available data on wind speeds from 1966 to 2005, with a few gaps. The hourly data consist of eight ASCII decodable data files, with details of contents explained. In this article, a relook at the available wind data, analysis of gust wind speeds recorded at various stations and probability of occurrence of wind speeds with a specific return period with proven methods of extreme value analysis techniques, are covered with a suggested revision for basic wind speed map.

Hourly wind data

As it is well known, wind speed in any region is highly variable naturally as well as owing to man-made industrial developments. For structural designs, even short-duration gusts are quite important because any structure has to withstand the short-duration extreme wind loads with a safe level of member stresses. The hourly wind speed records of 70 stations over different years in certain stations have a few gaps due to unavoidable stoppages in continuous operation of sensors and the recording instrumentation, power cuts and so on. According to the contemporary version of IS:875 codal provisions, strong winds with speeds over 80 kmph are generally associated with cyclonic storms. In the hourly wind database available with IMD, the daily gust wind peaks are assumed to include the cyclonic wind speeds as well, excepting regional tornado effects. It can be observed that a good number of meteorological observations are available in zones 2, 4 and 5. There seems to be no long-term measurements in zone 6, which is the highest wind speed zone. In most of the hourly wind-data stations, the peak gust wind is picked up from the daily trace of anemo-
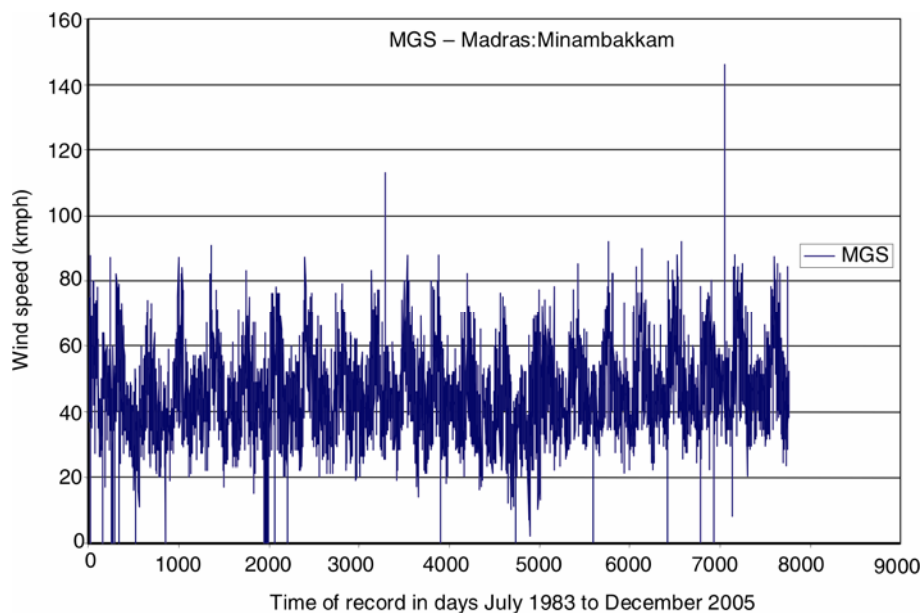
Figure 1. Distribution of daily gust wind speeds with some gap.

graph records. It is also to be noted that the continuity of data is limited in certain stations and missing gust wind data are also observed in some stations. The database of wind speeds from 43 stations up to the year 1982 has been used in the formulation of the present design wind speed map; this has not been significantly increased over the years. Out of the 70 IMD stations, about 56–58 stations have gust wind data at least for a few years up to 2005, with the newer stations having only less number of annual extreme wind-speed records. A typical extreme value analysis of the wind data of a selected station is discussed in the following section.

Review of extreme value analysis

In general, extreme value distribution of load and strength parameters of structural members and systems is important for reliable analysis of design of components and structures. For extreme wind speeds used in the design of structures, gust wind speed data should be available for many years for every possible geographic location to be specific. For the evaluation of wind loads on wind-sensitive structures, a regional design basis wind speed with a given return period is needed. These design wind speeds are derived from long-term record of wind gusts of specific region. Figures 1 and 2 show typical variation of daily gust wind speeds of Madras-Minambakkam station. The peaks are mathematically proved to be Raleigh-distributed for a parent with Gaussian process. Hourly gust wind data collected over every hour of a day for many years were observed to be neither stationary nor follow a Gaussian distribution in most of the stations. The zero wind speeds in Figures 1 and 2 pertain to data which are

not available for that hour or manifestation of a period of lull or 'NO-WIND'. Extreme values are in general observed to fit into one of the exponential/logarithmic asymptotic forms commonly recognized as Type-I, Type-II and Type-III. All the three forms can be represented by a single expression[3] given by a generalized extreme value (GEV):

$$G_X(x) = \exp\left\{-\left[1+\frac{\xi(x-\mu)}{\sigma}\right]^{-1/\xi}\right\}, \tag{1}$$

where μ, σ and ξ are the location, scale and shape parameters respectively, which define the characteristics of the extreme value distribution. These parameters have to be then evaluated from a valid database of fairly long-term annual wind-speed records. If $\xi > 0$, GEV is known as Type-II (Frechet) distribution with an unbounded upper tail $(\mu - \sigma/\xi < x < \infty)$. The case of $\xi < 0$ is called the Type-III (reverse Weibull) distribution, with a finite upper limit $(-\infty < x < (\mu - \sigma/\xi))$. As $\xi \to 0$, the Type-I Gumbel[7] distribution is obtained which is given by

$$G_X(x) = \exp\{-\exp[-(x-\mu)/\sigma]\}. \tag{2}$$

This distribution has been widely used for modelling extreme wave heights, annual maximum flood levels and annual maximum wind speeds to arrive at characteristic values with specific return periods, for engineering design of buildings and structures. With the shape parameter approaching zero, the distribution is defined with location and scale parameters which are to be estimated from long-term data pertaining to any geographic location/site. The usual methods of extreme value analysis are
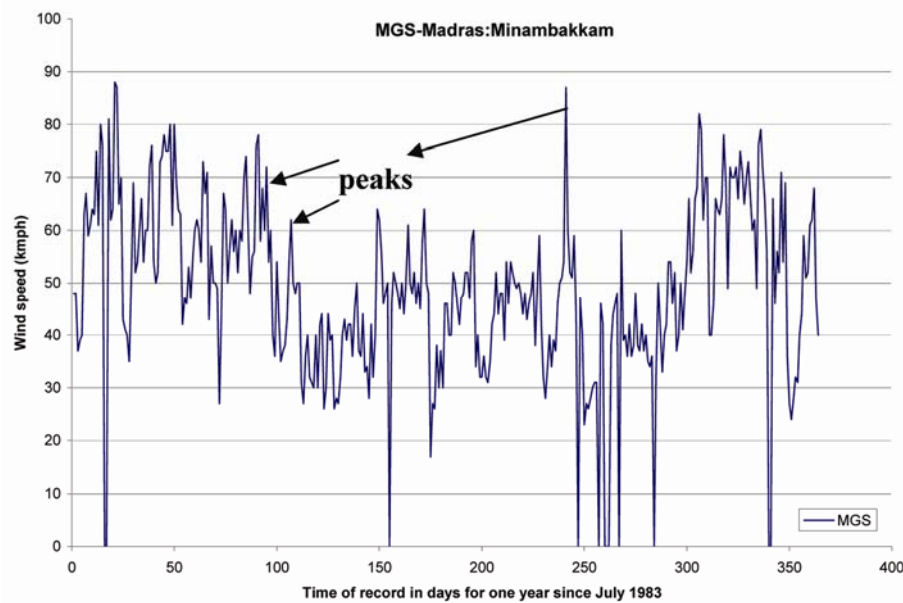
Figure 2. Peak distribution of daily gust wind speeds for one typical year.
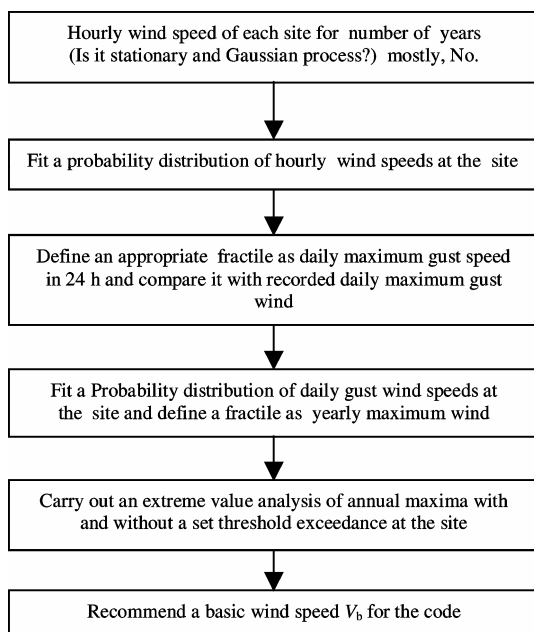

Figure 3. Issues in the evaluation of basic design wind speeds for a given return period.

those of moments, maximum likelihood method, order-statistics approach and Gumbel's probability paper approach. For the analysis of design wind speed estimates, the National Building Code of Canada (NBCC) has adopted[3] the peaks-over threshold (POT), r largest order statistics approach (r-LOS) and Annual Maximum Gumbel (AMG) methods. The authors concluded that the (r-LOS) is preferable over the other two methods and is more versatile since it has lower sampling variability associated with its extreme quantile (parameter) estimation. In this

study a proven method of order statistics[8,9] is utilized, ensuring an unbiased and minimum variance estimator for a given sample size and exceedance probability, in Gumbel's probability paper format. The various issues of evaluating a design basis wind speed from hourly wind data are given in Figure 3.

Method of moments

In this method, the sample mean and sample variance are mathematically related to the location, scale and shape parameters of the GEV distributions. This method is an approximation of the probabilistic integral-based approaches. Using the statistical relations of sample moments to the distribution parameters, the distribution can be realized. In the case of inadequate number of samples, it is possible to simulate additional samples using Monte Carlo techniques, according to the fitted probability distribution. However, the simulated data will be biased on the sample moments and the statistics. Thus the occurrence of high wind speeds, their arrival sequence or the return period will not be realistic. When the sample data are long enough, this method of simulation may result in the right characteristic values. Based on this method an interactive computer program in VC[++], for site-specific cyclonic wind data processing has been developed at SERC[10,11].

Method of order statistics

When the sample size is considerably small, such as the annual measured maxima of wind speeds at any given location, the method of moments approach may predict

the characteristic wind speeds of a given return period based on poorly fitted extreme value distribution. This results in large variance in the simulated occurrence of wind speeds. A method based on the theory of order statistics was developed by Lieblein[12], which is based on a linear function of a set of ordered values such as random wind speeds ($U_1, U_2, \ldots, U_r$), that is,

$$L = \sum_{i=1}^{r} w_i U_i, \tag{3}$$

where $U_1 \leq U_2 \leq \cdots \leq U_r$, and w_i are weights that may be decomposed into

$$w_i = a_i + b_i s_p, \tag{4}$$

where s_p is the value of the standardized variate S at an exceedance probability p; that is,

$$\exp(-e^{-s}) = 1 - p \quad \text{or} \quad s_p = -\ln[-\ln(1-p)]. \tag{5}$$

Then the estimator given in eq. (3) becomes

$$L = \sum_{i=1}^{r} [a_i U_i + (b_i U_i) s_p], \tag{6}$$

where the weights a_i and b_i are functions of 'r' and 'p', and the following conditions are imposed:
The expectation of L,

$$E(L) = u_r + \frac{1}{\alpha_r} s_p, \tag{7}$$

and the variance of L,

$$\text{Var}(L) = \text{minimum}. \tag{8}$$

In view of eqs (6) and (7), the unbiased minimum variance estimators for u_r and α_r are given as[8]:

$$\hat{u}_r = \sum_{i=1}^{r} a_i U_i, \tag{9}$$

$$\frac{1}{\hat{\alpha}_r} = \sum_{i=1}^{r} b_i U_i, \tag{10}$$

Lieblein[12] obtained the relevant set of weights to be used for values of $r = 2$–6 for the exceedance probability of over 90% (i.e. $P \geq 0.90$) and also concluded that the relative efficiency of the estimator is over 80% only when $r = 5$ or 6. He recommended that for sample sizes greater than 6, the entire set of sample space should be divided into subgroups of five or six, and the remainder in another subgroup. This is based on the assumption that the set of extreme values constitutes a statistically independent series of observations, which must be preserved while implementing this method. Usually the original data sequence of the gust wind series would satisfy this requirement. The method given by Ang and Tang[8] was coded in MATLAB[13] script language and a program developed for the extreme wind data analysis. The number of years of hourly wind data availability varied from site to site. Hence the program takes interactively an option from the user, to enable the choice of the subgroup size (five or six) so that the remainder subgroup size is non-zero. Within the subgroup of extreme wind speeds, the data are arranged in increasing order according to Lieblein's requirement. In order to avoid repeating annual maximum wind speed data, a random number generating scheme was used to marginally adjust the repeating data, from being not exactly equal. While assuming Gumbel probability distribution, the ratio of sample rank to sample size fixes the probability of occurrence of any wind speed. Hence repeating data need to be fitted for prediction, with marginally differing probabilities. Some of the results of this analysis are discussed here.

Results of extreme wind data analysis

The hourly wind database has been scanned for individual stations based on their specific identification number and the gust wind data pertaining to every available wind monitoring station have been separated into unique named files for statistical analysis. A typical plot of the long-term daily gust wind is shown in Figure 1. It may be observed that there are several days with either null or zero gust wind (no data available) recorded at the Madras-Minambakkam station.

This is evident in the histogram given in Figure 4 a. To be realistic for design purposes (peaks over the mean are important), the up-crossing peaks shown in the zoomed view of one-year daily gusts with peaks over the mean given in Figure 2 were considered and their distribution is shown in Figure 4 b. The zero values and down-crossing valley points were eliminated in the count and only positive up-crossing peaks were gathered during the period of data collection. A high-resolution time history (say, 10–20 samples/s) of wind data at any given site is not available for long periods (in years), which is a limitation unavoidable even in developed countries. In general, if the synoptic wind speed has been a stationary and Gaussian process, only then the extreme peaks could follow a Raleigh distribution. It could have been stationary for a short duration, i.e. 10 min to 1 h, but is unlikely to be stationary for the entire day or, for days, or for years. Hence, the daily gust wind data available at every station are with some limitations of sophistication in the instrumentation, data-collection reduction and recording. For completeness, simple statistical details of the available daily
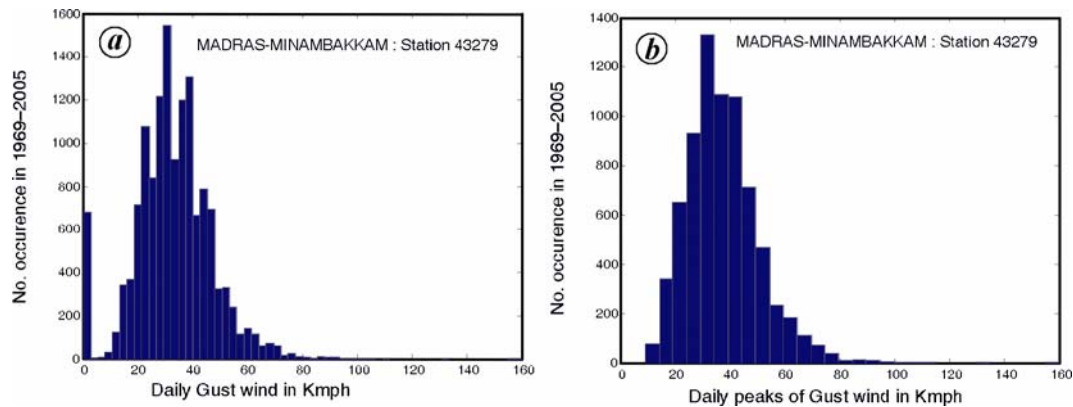
Figure 4. Histogram of daily gust/peak wind speeds of IMD database.

gust wind speed records for all the IMD stations are given in Table 1. The peaks are not likely to have uniform spacing because of synoptic as well as monsoon wind climates. The arithmetic mean of the gust hourly wind speed data of IMD and of the peaks is given in Table 1. Their standard deviations and probable peak values are given in the columns marked as 'Extreme', with the assumption of the threshold peaks being the sum of the mean plus three times the standard deviations. There is always an ambiguity in this statistical analysis as the predicted extreme wind speeds include both data from synoptic as well as monsoon winds, since they span several days of many years of data. It has been observed in most of the IMD stations that the difference of extremes predicted using all the gust wind statistics as well as up-crossing peak order statistics is marginal.

The total counts of the daily records in individual stations indicate the number of years of data available in the site. More than ten stations have maximum gust speed (MGS) data less than 4–5 years, which are not useful for design wind prediction.

Most of the gust wind speed records being from synoptic/monsoon winds, it is likely to be highly variable from site to site. Based on statistical scatter of gust wind statistics and up-crossing peak wind characteristics, Figure 5 provides part of the scatter of 'mean gust wind speed' (G-mean of 14,098 samples for Madras Minambakkam, from July 1983 to 2005 shown in Figure 1) vs gust peak (which is the mean gust plus three times its standard deviation), peak–peak (which is the mean of 7374 peaks (indicated typically in Figure 2) plus its standard deviation). There is close to 80% coefficient of determination of mean of peaks (EP-mean) and peak of peaks in the measured met-sites in India with the respective G-mean.

Case study of site-specific design wind speed

To arrive at the method of evaluation of site-specific design basis wind speed using the limited long term

annual (MGS) wind data available, the method of order statistics described earlier with 5 or 6 in each sub-group, and with a remainder sub-group having less than 5 or 6, has been implemented using MATLAB script program. The Madras-Minambakkam dataset having 41 years of data has been illustrated as a typical case study. The data span from the year 1969 to 2005; part of the data from July 1983 is shown in Figure 1 and is distributed as shown in Figure 4. There have been few years of repetition using probably additional instruments in the gust wind data. If these additional data belonged to the same station number, they were merged in one dataset for analysis.

Gumbel's probability paper approach was adopted and the arrival sequences of extreme wind data according to the available records were preserved. The MATLAB script file developed for the analysis has the options to choose any one station data or to process all the station data. It also facilitates the probability plots with predicted characteristic wind speeds for 50-year return period. The Gumbel's probability paper approach resulted in the estimation of the scale and location parameters by graphical evaluation of the intercept and the slope of the fitted straight line on the probability paper. The Gumbel fitted annual extreme wind speed from the annual hourly data as given in the IMD database is shown in Figure 6. The predicted value was around 126 kmph for a mean return period of 50 years, which is about 35 m/s. The dotted line above the mean line in Figure 6 gives the upper confidence limit of 84.13%, corresponding to 1σ variation of the predicted maximum wind speeds, which in this case is about 37 m/s. The zonal classification in IS:875 is zone 5, which corresponds to 50 m/s. Use of all the annual hourly data gives a lower design basis wind speed. Figure 6 shows horizontal scatter in the plots owing to repetition of data in the measured period of 41 years. To get a linear fit in the probability plot minor adjustments to the repeating data have been carried out manually avoiding exact repetition. The resulting plot is shown in Figure 7, which gives a prediction of slightly higher wind speed than the unadjusted values. Further improvements in the straight-

Table 1. Statistics of daily gust wind data at IMD stations in India

|	Total no. of records	Available number of years of maximum gust wind speed	Raw hourly gust statistics (Figure 1)				Up-cross peak statistics (Figure 2)			
			W_{max} kmph	Wemean kmph	Westd kmph	Extreme kmph	Number of peaks	EP-mean kmph	EP-Std kmph	ExtremeP kmph
IMD station	Count	A	B	D_m	D_{std}	D_{peak}	Count	E_m	E_{std}	E_{peak}
HASHIMARA	2882	9	125	31	13	72	1386	24	15	68
MADRAS_HARBOUR	6177	20	150	42	13	81	3045	35	17	85
TUTICORIN_HP	5275	15	140	51	14	94	2833	47	16	95
MANGALORE_HP	1451	4	91	38	13	76	761	35	12	70
AMRITSAR	11099	32	190	37	19	94	5921	31	17	82
PALAM_A	12626	35	199	39	15	85	6792	34	14	78
NEWDELHI_SAFRJG	12310	34	152	35	15	79	6457	30	14	71
CHABUA_A	395	2	72	28	12	65	155	16	15	60
JAIPUR_SANGANER	11697	38	181	32	15	76	6148	27	14	70
LUCKNOW_AMAUSI	7160	18	170	39	16	87	3637	33	16	81
BAGHOGRA_A	2921	9	102	31	13	70	1448	24	15	68
ALLAHABAD_BAMHRAULI	863	3	131	31	14	73	452	27	13	65
VARANASI_BABATPUR	539	2	67	25	9	52	277	21	9	49
GAYA	2207	7	120	34	16	83	1163	29	16	76
NEW_KANDLA	7407	22	132	47	15	91	3989	43	15	88
AHMEDABAD	9652	29	150	35	11	69	5019	31	12	68
BHOPAL_BAIRAGARH	7784	22	125	42	14	83	4158	38	13	78
JAMNAGAR_A	4328	15	182	44	13	83	2209	38	16	86
BARODA	7564	22	155	35	13	72	4052	31	13	70
INDORE	6959	21	136	52	13	91	3704	47	15	92
JAMSHEDPUR_PB	1395	4	118	34	18	89	730	29	16	78
JAMSHEDPUR	1284	4	122	36	17	87	646	30	17	79
KALAIKUNDA_A	2536	8	142	40	17	91	1283	33	18	87
CALCUTTA	6074	18	143	40	16	88	3133	35	16	82
CALCUTTA_DUMDUM	9966	29	200	34	17	83	5272	29	15	75
NAGPUR_ONEGAON	9348	26	132	36	15	81	5013	32	14	74
RAIPUR	6442	22	112	28	13	67	3443	24	12	61
JHARSUGUDA	1216	4	120	37	17	89	657	32	16	80
SAGAR_ISLAND	6603	19	163	31	16	79	3458	26	15	73
VERAVAL	4427	16	150	40	12	77	2341	35	14	77
BOMBAY_SANTACRUZ	13616	38	200	36	10	67	7262	33	10	64
AURANGABAD_CHIKATHA	394	2	52	32	8	56	117	15	16	64
JAGDALPUR	3438	11	125	33	13	73	1764	28	13	67
GOPALPUR	3764	11	140	43	15	89	1999	39	15	83
BOMBAY	12530	36	103	37	12	74	6649	34	13	72
PUNE	13410	38	165	34	10	66	7116	31	11	64
PUNE_ALOHAGAON	4253	14	130	46	13	85	2210	41	16	88
BIDAR_A	3321	10	137	46	15	90	1557	36	20	96
HYDERABD_A	9291	28	140	37	13	77	4845	34	13	73
HAKIMPET_A	4161	12	114	44	14	87	2146	39	15	83
VISHAKHAPATNAM_A	6211	18	196	43	14	85	3198	39	14	79
VIZG_RSRW	3754	13	140	34	13	72	2079	31	12	68
MORMUGAO	12549	37	190	35	14	77	6542	31	14	74
YELAHANKA_A	1332	4	124	43	18	96	674	36	20	95
MADRAS	761	3	98	32	10	61	396	30	9	57
MADRAS_MINAMBAKKAM	14098	41	160	38	13	77	7374	33	14	75
MANGALORE_HP_PANBUR	9875	28	110	31	12	67	4818	25	14	66
BANGALORE	11319	32	106	38	10	69	5965	34	12	70
NAMGALORE_A	10969	32	125	41	11	75	5738	37	12	74
TAMBARAM_A	4844	5	104	45	12	79	1677	24	23	92
PORT_BLAIR	10253	29	170	40	17	89	5575	36	16	84
KODAIKANAL	13183	37	190	40	12	76	6453	33	16	81
TIRUCHIRAPALLI_A	13261	37	167	50	15	95	6928	46	15	92
COCHIN_NAS	9418	29	180	36	12	72	4929	32	13	70
TRIVANDRUM_TIRUAN	9908	29	108	29	11	61	5655	27	11	60
TRIVANDRUM_A	7976	25	92	30	11	64	4387	27	12	63
TUTICORIN	7761	23	146	49	13	87	4111	45	13	84
OZAR	2825	7	102	42	15	86	1494	37	16	87
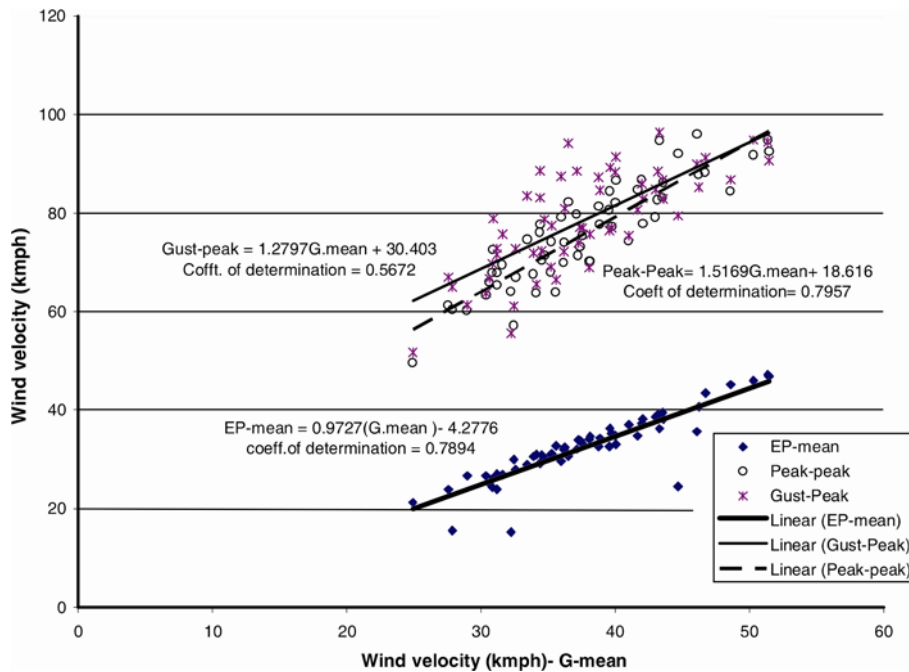
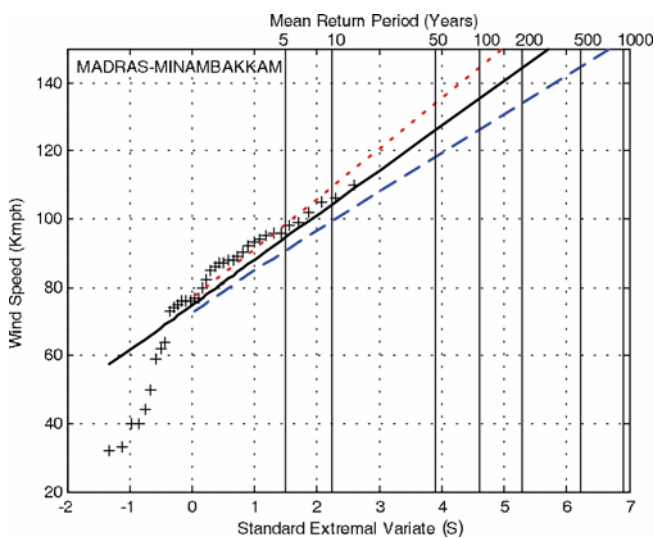**Figure 5.** Variation of peaks and mean of peaks with gust mean.

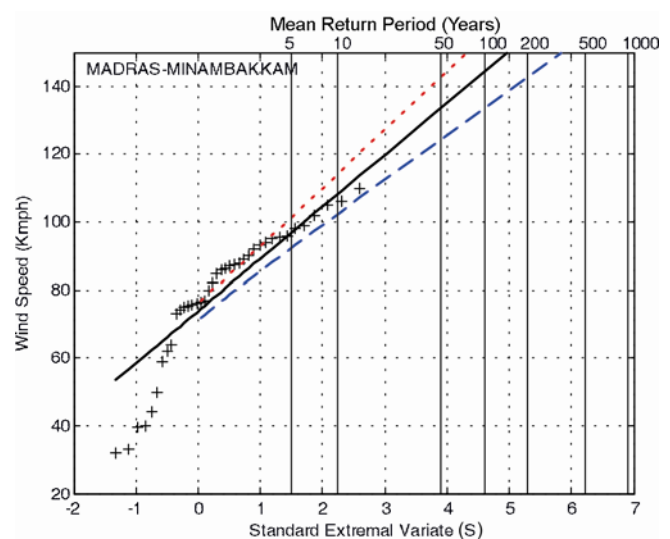**Figure 6.** Gumbel's probability plot of original IMD data without correction.

Figure 7. Gumbel's probability plot of IMD data with manual adjustment of repeating data.

line fitting of the Gumbel plot was achieved using a threshold speed of 50 kmph (Figure 8), which is about 65% of the 'Extreme P' value computed (given in the last column E_{peak} of Table 1 for the individual stations) using the daily gust wind speeds recorded in the stations. The predicted value is 136 kmph for a mean return period of 50 years. The predicted design wind speed of 38 m/s is lower than the current value specified in the code by about 30%. This is because the IMD data are prepared from manually picked instantaneous values recorded in automatic strip chart recorders. Figures 9 and 10 are obtained using random adjustment of repeating wind

speed data, without and with the use of threshold wind velocity of 50 kmph. The variations were minimum; they were within 8% and in the range 35–38 m/s. Based on discussions with IMD, this gust wind in general is the wind speed sustained over 1–2 min duration. Hence, the corresponding basic wind speed, i.e. 3 s gust wind speed can be obtained by multiplying the predicted value with a wind gust factor of $Gv(3)/Gv(60)$ or $Gv(3)/Gv(120)$ for terrain category 2 and at 10 m level as given below.

$$Gv(t) = 1 - 0.59(0.15)^{1.13}\ln(t/3600). \qquad (11)$$

The values of $Gv(3)$, $Gv(60)$ and $Gv(120)$ were calculated as 1.49, 1.283 and 1.235 respectively. Hence for wind sustained over 1 min, the wind gust factor was obtained as $Gv(3)/Gv(60) = 1.16$. For the case of 2 min sustained record, the factor was $Gv(3)/Gv(120)$ and calculated as 1.21. Thus the corresponding basic wind speeds will be 44 or 46 m/s taking a conservative upper limit of predicted wind speed of 38 m/s for the station in consideration. Based on the uncorrected annual maximum gust wind speeds (from daily values MGS; Figure 6), the predicted basic wind speeds for the IMD stations are given in Table 2. The revised basic wind speed for the purpose of design is given with a uniform factor of 1.16, assuming 1 min sustained wind. Assuming the validity of the factor 1.16 to be applicable for all the stations, the percentage dif-

ference in the contemporary practice and the suggested basic wind speed is shown in Table 2.

Based on the random adjusted repeating wind speeds, and using a factored (65%) site-specific peak wind (mean + 3 SD) as a threshold wind speed, the Gumbel probability plots were re-worked (as given typically for Madras-Minambakkam site in Figure 10), and the results are also given in Table 2. While there was marginal change in the differences in various stations, the Gumbel fit was quite realistic in most stations with annual maxima of wind speeds scattered within the confidence level lines in the probability paper. It has been observed that stations having lesser years of wind speed data have considerable spread in the Gumbel fit. The order statistics approach as implemented in the MATLAB script program showed repeatability and the predicted 50-year return period wind speeds were sensitive when the sub-group size was not '6', in the sampled original sequence of data of annual maximum winds as suggested by Lieblin[12]. The efficiency of this computation was highest when the sub-group was of order '6'. The efficiency was reduced when the sub-group had to be chosen as '4' or '5' owing to lack of data. The MATLAB program interactively prompts for the choice of the sub-group size depending on the number of years of data available at a given site. The results given in Table 2 are based on the Gumbel probability fits of site-specific data. It may be noted that the sites which have less than 7 years of wind data were not considered for the study. All the available annual maximum wind data with and without a site-specific threshold have been used to suggest a revised basic wind speed V_{bR}, along with its percentage difference, i.e. $((V_b - V_{bR})*100/V_b)$ with respect to the existing basic wind speed given in IS:875. Table 2 suggests that the wind speeds may have to be revised upward in certain locations and most other locations which
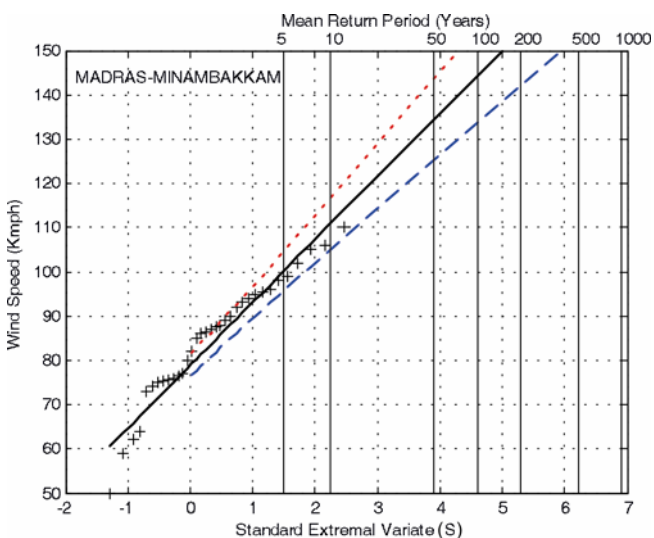

Figure 8. Gumbel's probability plot of IMD data with manual adjustment of repeating data using a threshold wind speed of 50 kmph.
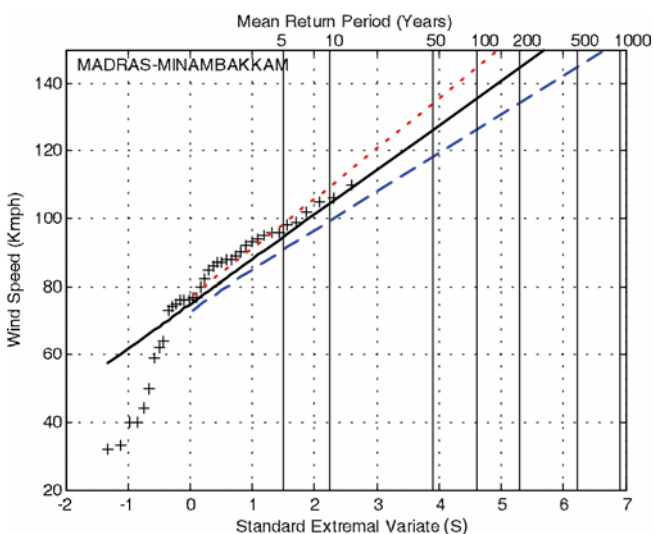

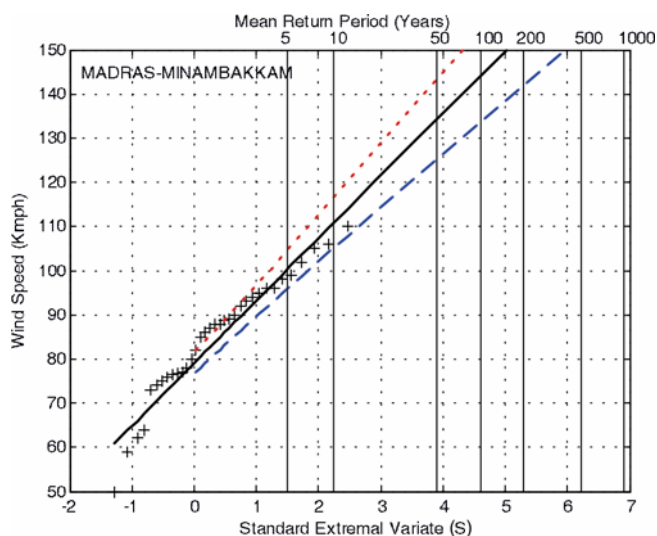**Figure 9.** Gumbel's probability plot of IMD data with random adjustment of repeating data.

Figure 10. Gumbel's plot of IMD data with random adjustment of repeating data using a threshold wind speed of 50 kmph.

Table 2. Design basic wind speed (m/s)/wind zone for various IMD meteorological stations (with all annual maximum wind speeds or values over threshold)

Station ID	Wind zone IS:875	Basic wind speed IS:875 V_b (m/s)	Prediction with Gumbel using all annual peak values			Prediction with Gumbel using annual peak values over the threshold		
			V_{bR} (m/s)	Wind speed with $T = 50$ yrs	Percentage difference IS:875	V_{bR} (m/s)	Wind speed with $T = 50$ yrs	Percentage difference IS:875
AHMEDABAD	2	39	42	36	8	43	37	10
AMRITSAR	4	47	54	47	16	56	48	19
BAGHOGRA(A)	4	47	42	36	−11	42	36	−11
BANGALORE	1	33	30	26	−9	34	29	−4
BARODA	3	44	41	36	−6	42	37	−4
BHOPAL BAIRAGARH	2	39	49	42	26	45	39	16
BIDAR (A)	2	39	51	44	30	52	45	33
BOMBAY	3	44	32	28	−27	33	28	−26
BOMBAY/SANTACRUZ	3	44	39	34	−11	40	35	−8
CALCUTTA	5	50	46	40	−7	48	41	−5
CALCUTTA/DUM DUM	5	50	52	45	4	54	46	7
CHABUA (A)	5	50	–	–	–	–	–	–
COCHIN (N.A.S)	2	39	43	37	10	44	38	14
GAYA	2	39	39	33	−1	56	48	44
GOPALPUR	2	39	46	39	17	47	40	20
HAKIMPET (A)	3	44	59	51	33	–	–	–
HASHIMARA (A)	4	47	48	41	2	50	43	6
HYDERABAD (A)	3	44	40	34	−10	41	35	−8
INDORE	2	39	47	40	20	42	36	7
JAGDALPUR	2	39	44	38	14	46	39	17
JAIPUR/SANGANER	4	47	45	39	−4	46	40	−2
JAMNAGAR (A)	5	50	46	40	−8	40	35	−19
KALAIKUNDA (A)	5	50	58	50	17	55	47	9
KODAIKANAL	2	39	41	36	6	41	35	4
LUCKNOW/AMAUSI	4	47	54	47	15	55	48	17
MADRAS/MINAMBAKKAM	5	50	39	34	−21	45	39	−10
MADRAS HARBOUR	5	50	46	40	−8	53	45	5
MANGALORE H.P./PANAMBUR	2	39	40	35	3	38	33	−3
MORMUGAO	2	39	40	35	4	42	36	7
NAGPUR/SONEGAON	3	44	43	37	−2	49	43	12
MANGALORE (A)	1	33	34	29	2	36	31	10
NEW DELHI/SAFDJNG	4	47	45	39	−3	47	40	0
NEW KANDLA	5	50	45	39	−10	46	40	−8
OZAR 2	39	52	45	33	–	–	–	
PALAM (A)	4	47	53	45	12	54	47	15
PORT BLAIR	3	44	47	40	6	48	41	9
PUNE 2	39	36	31	−9	42	36	6	
PUNE (A) LOHAGAON	2	39	48	41	22	50	43	28
RAIPUR	2	39	43	37	10	45	39	16
SAGAR ISLAND	5	50	52	45	3	53	46	6
TAMBARAM (A)	5	50	45	39	−10	–	–	–
TIRUCHIRAPALLI (A)	4	47	48	41	2	49	42	3
TRIVANDRUM (A)	2	39	33	28	−16	34	29	−14
TRIVANDRUM/TIRUVN	2	39	29	25	−25	30	26	−22
TUTICORIN	2	39	36	31	−6	38	32	−4
TUTICORIN H.P.	2	39	39	34	0	41	35	5
VERAVAL	5	50	43	37	−14	45	38	−11
VISHAKHAPATNAM (A)	5	50	49	42	−3	50	43	0
VIZG RSRW	5	50	49	43	−1	51	44	3

have variations of around 10% may be ignored while considering a wind speed revision either to higher or to a lower wind zone. Figure 11 shows schematically the details given in Table 2, with red circles indicating a revision upward and blue circles demanding no revision of the current wind zone.
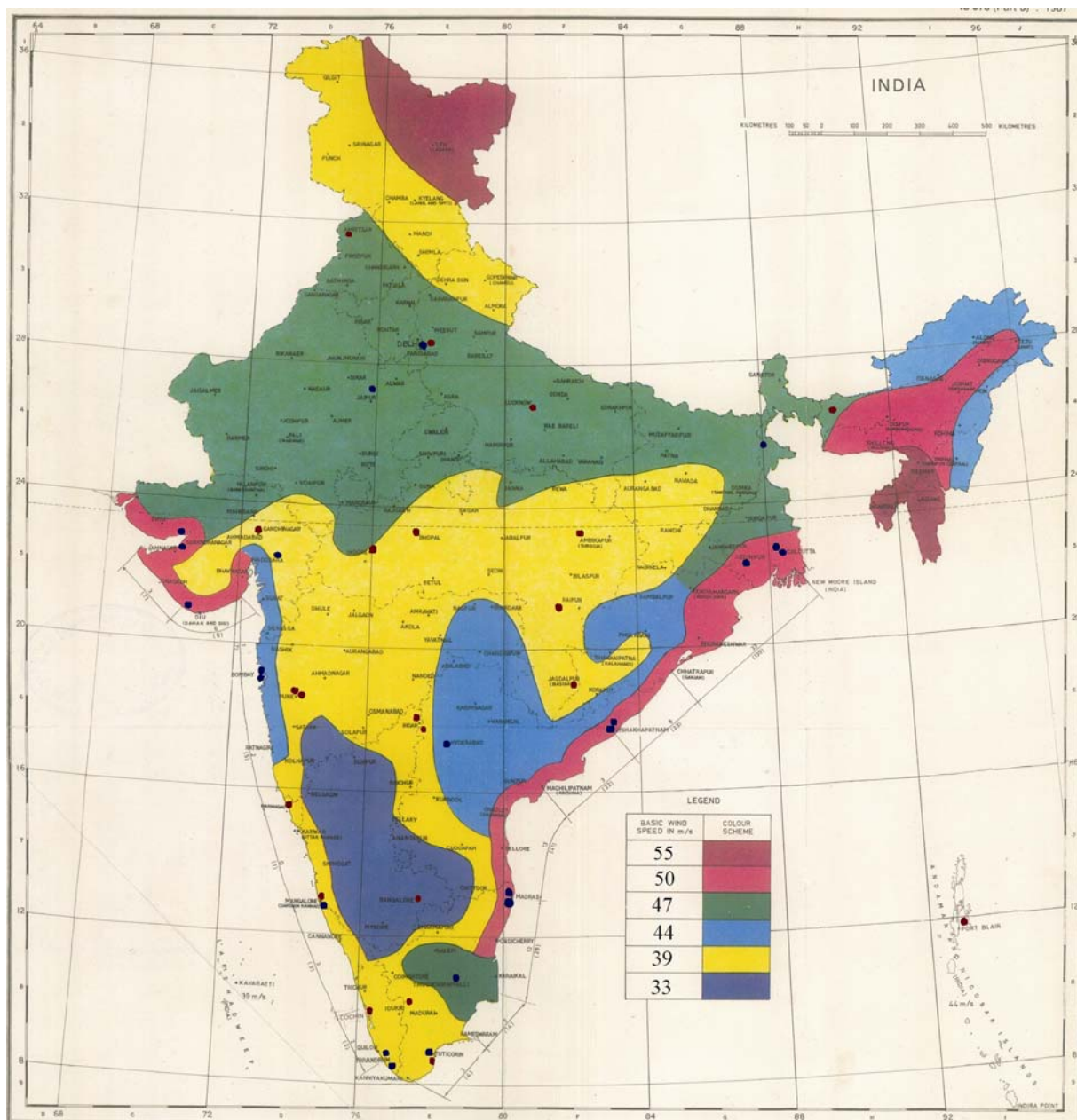
Figure 11. Design wind speed map with updated data at 45 IMD stations.

Revised wind speed map

While preparing the revised map, the validity of the existing map was broadly accepted. Whenever the codal recommendations were conservative, they were not altered. In regions where there was an increase up to 10%, these were also not altered. Only significant increase in certain stations has been used to suggest modifications. While preparing a codal recommendation it is necessary to broadly identify the regions which require change, as in-

dicated in Table 3. Amritsar, Delhi and Lucknow have shown significant increase in wind speed. Hence a belt of 50 m/s was included in the existing map having a basic wind speed of 47 m/s (upgradation from zones 4 to 5). Similarly, increase from 44 to 47 m/s has been suggested adjoining the cyclone-prone east coast in the regions of Andhra Pradesh and Orissa. There are some other minor deviations, particularly with respect to wind zone 2 (39 m/s). The revised wind zone map is given in Figure 12. The individual cities/sites having higher spot values need to
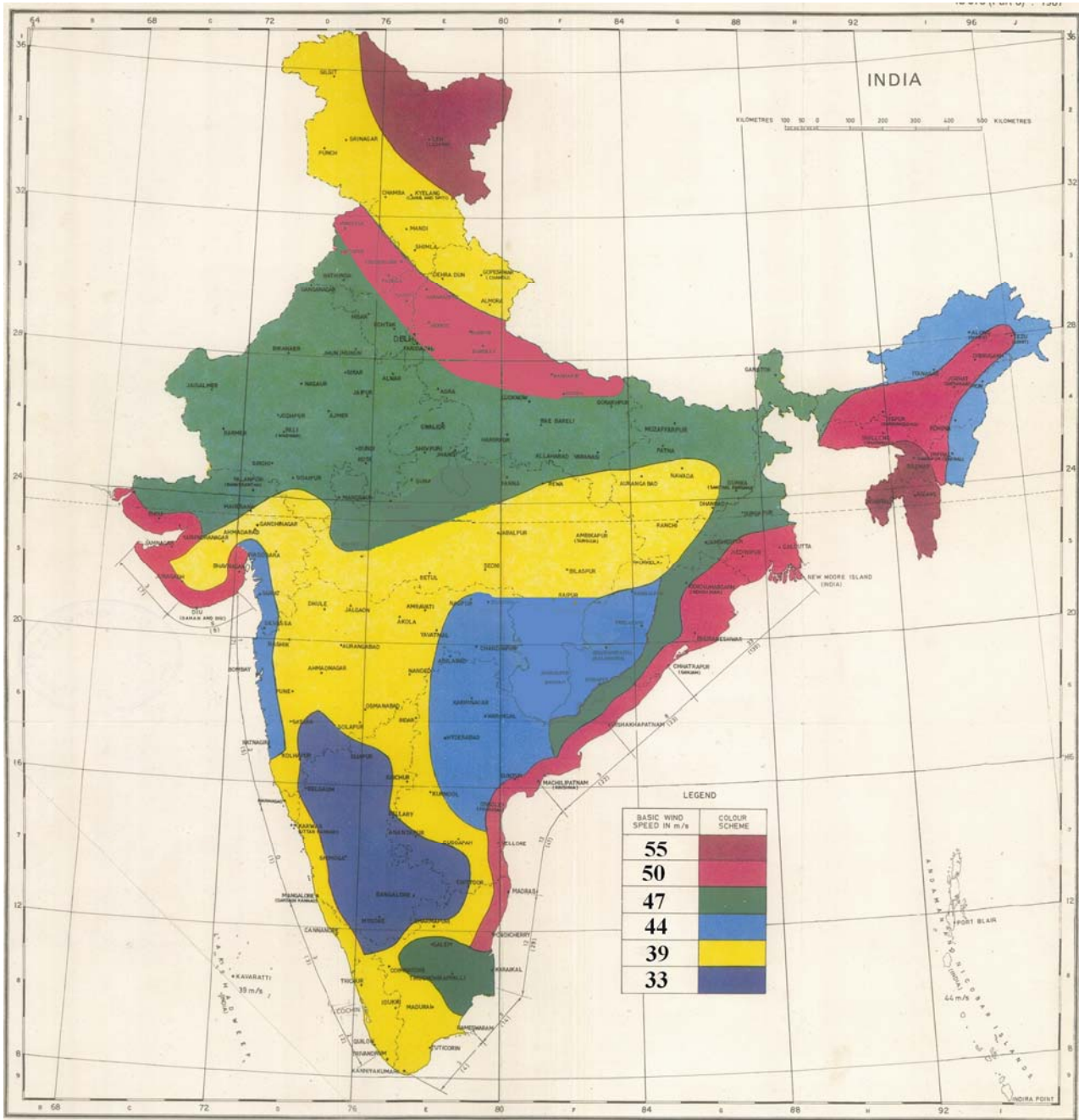
Figure 12. Suggested modification of design wind speed map of India.

Table 3. Suggested re-zoning based on important IMD meteorological stations

Station	Present wind zone IS:875	Present existing design wind speed (m/s)	Revised wind zone IS:875	Suggested design wind speed (m/s)
AMRITSAR	4	47	5	50
BHOPAL_BAIRAGARH	2	39	4	47
BIDAR_A	2	39	3	44
JAGDALPUR	2	39	3	44
LUCKNOW_AMAUSI	4	47	5	50
NEWDELHI_PALAM_A	4	47	5	50
RAIPUR	2	39	3	44

be used by the designer for important structures with subjective insight and choice. In the recent years IMD has established[14] several HWSR (high wind speed recorders) stations with sonic anemometer and internet protocol, which will be useful in future, to capture accurately the gust winds in synoptic as well as pressure systems (cyclone winds). Several government/private agencies such as Centre for Wind Energy Technology, Power Grid Corporation of India Limited, and Tata Energy Research Institute are collecting meteorological data for various other purposes, which may be pooled for more effective and rational micro-zonation of wind speed map of India.

Conclusion

The wind speed data available in 70 meteorological stations have been studied for obtaining the basic wind speed. Based on the scientific analysis of data, certain regions require upgradation to higher wind zones. A revised basic wind speed map for the country has been suggested.

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