Extreme value analysis of Fiji's wind records

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ABSTRACT

A number of extreme value analysis techniques are utilised to predict basic design gust wind speeds for Fiji, which lies in a tropical cyclone prone region. The study shows that a number of modern methods tend to highly under-predict extreme wind speeds in regions of Fiji severely affected by tropical cyclones, although their skills improve in less severely affected regions. The reference for comparison was Dorman's method, which has been previously used as a guidance for development of Region D wind speeds in the Australian wind loading code – the AS1170.2-1989. In the case of Fiji, this study recommends the AS1170.2-1989 Region C provisions for Suva and the eastern coasts of the main island of Viti Levu only, and the AS1170.2-1989 Region D provisions elsewhere. This is significantly different to the provisions of the current National Building Code of Fiji (1990) which allow for the use of AS1170.2-1989 Region C provisions for all of Fiji. This difference is attributed to differences in the frequency and intensity of tropical cyclones visiting Fiji as compared with those for Australian Region C.

Keywords: *Design gust wind-speed, Extreme value analysis, Tropical cyclone, Wind loading code.*

1 INTRODUCTION

The wind resistant design of buildings and structures rely upon basic design gust wind speed provisions in wind loading codes. Such data is normally derived from extreme value analysis of parent wind data available from meteorological records over many years. A number of extreme value analysis (EVA) techniques are presently available for such purpose. These include the traditional Gumbel method, Dorman's (modified Gumbel) method, Generalised Pareto Distribution (GPD), Cooks Method of Independent Storms (CMIS) and the Vickery-Gomes (VG) method. The methods of GPD, CMIS and VG have been previously used for prediction of design gust wind speeds in regions affected predominantly by thunderstorms and extra-tropical storms, for example as described in the study of Holmes and Moriarty (1999). As far as prediction for tropical cyclone affected regions are concerned, the Australian wind loading code – the AS1170.2-1989 (1989) (and its successor – the AS/NZS1170.2 2002) utilise evidence based on Monte Carlo simulations, with guidance from a modified form of Gumbel, namely the Dorman method.

Fiji lies in a tropical cyclone affected region and wind–resistant design of buildings and structures is therefore inherent in the National Building Code of Fiji (1990). Whilst this code for the most part refers directly to the AS1170.2-1989 in the assessment of wind loads, it nevertheless has its own provisions with regards design gust wind speeds and terrain categorisation. More specifically, it utilises the Australian Wind Region C (see Figure 1) basic design gust wind speeds for the entire group of islands in Fiji. The only basis for doing this is the belief that Fiji is affected by tropical cyclones of similar characteristics to those affecting Wind Region C of Australia. It is unfortunately not based upon any analysis of Fiji's own historical wind data. In the absence of the required analysis and data, this appears to be a sensible approach. However a re-examination of the climatology of extreme wind speeds and frequency and intensity of tropical cyclones in Fiji, in comparison with those for Australia (Neumann 1993) suggests that this procedure is perhaps non-conservative. For example, Figure 2 shows that over a period of 30 years, Fiji was affected by 40 tropical cyclones, while Australian Wind Region C by about 20 and Australian Wind Region D* by more than 40. This fact alone suggests a higher probability of exceedence of given wind speeds can be expected in Fiji when compared with that for Australian Wind Region C.

Past wind speeds recorded during intense tropical cyclones at station Nadi in Fiji, shown in Table 1 (Revell 1981; Kerr 1976), also suggest that the ultimate limit states basic design gust wind speed V_u of 70 m s^{-1} (which is applied to all regions in Fiji) has been exceeded as well.

In light of the above, there is an urgent need to derive realistic design wind speed data for Fiji using its own historical wind records. This paper therefore seeks to implement different extreme value analysis methods in an attempt to generate such data for use in the National Building Code of Fiji. In conducting extreme value analysis of wind records from Fiji, there is opportunity for two additional types of investigation: Firstly, the effectiveness of different extreme value analysis methods for a region affected by tropical cyclones can be investigated. Secondly, since parent wind data are available from five geographically different stations as shown in Figure 3, that represent areas of varying tropical cyclone intensity (as will be shown in section 4), the relationship between gust wind speeds and storm intensity, if any, could be identified.

2 EXTREME VALUE ANALYSIS (EVA) METHODS

2.1 GENERALISED EXTREME VALUE DISTRIBUTION (GEVD)

If a sample consisting of the annual maxima is obtained from parent Weibull or Rayleigh distributions, the form of the wind speed distribution described by the

Generalised Extreme Value Distribution (GEVD) is given by:

$$F_v(V) = \exp\left\{-\left(1 - \frac{k(V-u)}{a}\right)^{1/k}\right\} \qquad (1)$$

In Equation (1), k is a shape factor. There are three cases of k: $k = 0$, $k < 0$ and $k > 0$. These three cases give rise to what is commonly known as Type I, Type II and Type III GEVD's respectively. For the case $k = 0$, interpreted as the limit $k \to 0$, the Generalised Extreme Value Distribution becomes:

$$F_v(V) = \exp\{-\exp(-a(V-u))\} \qquad (2)$$

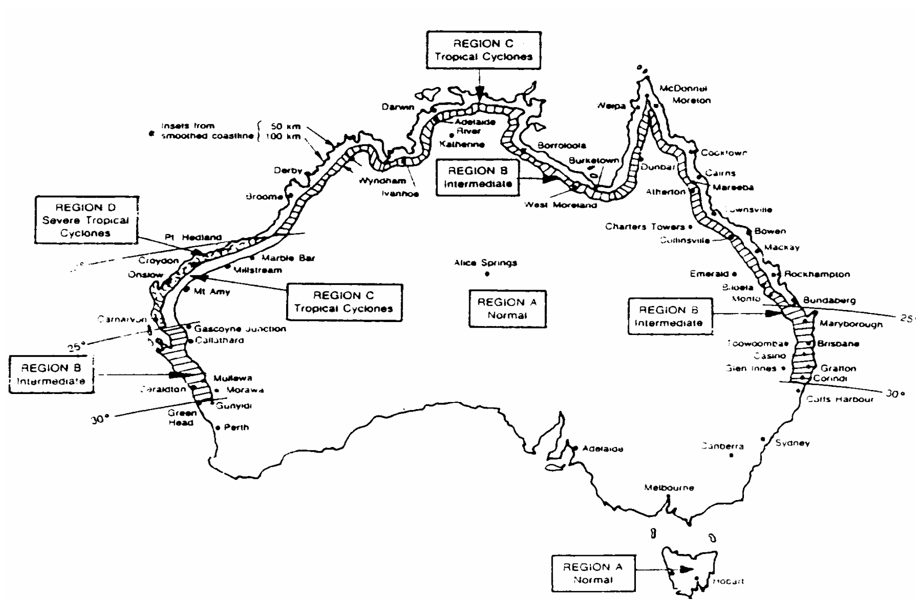

Figure 1. Australian wind regions from the AS1170.2-1989 (1989).

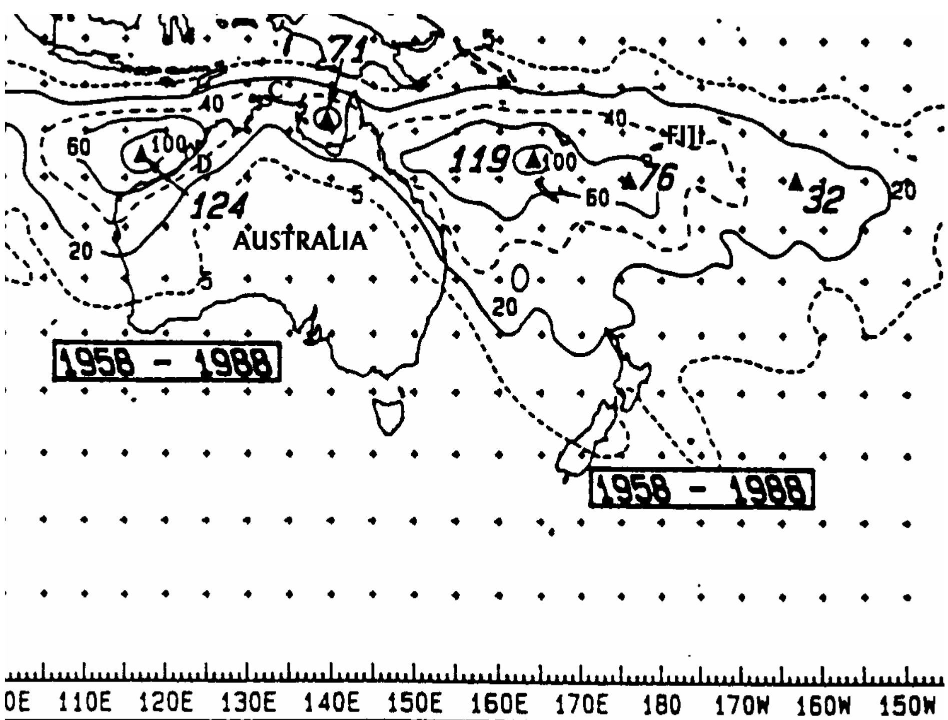

Figure 2. Frequency of tropical cyclones affecting Australia and Fiji, from Neumann (1993).

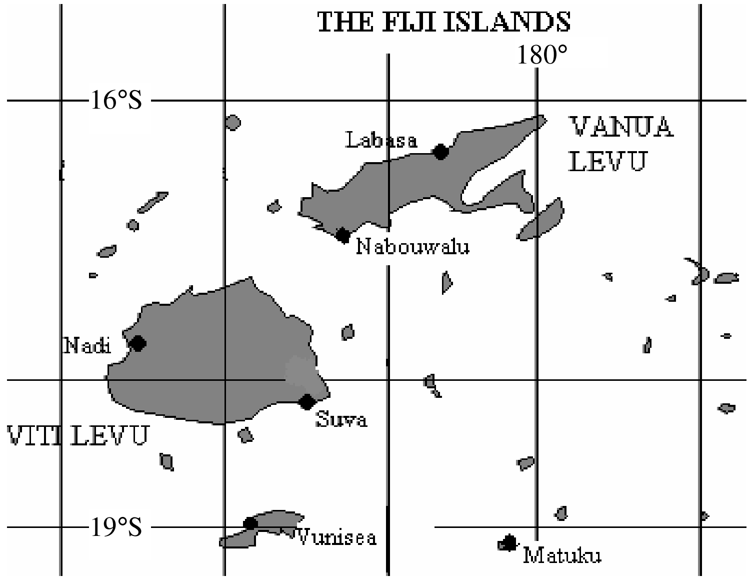

Figure 3. Meteorological stations in Fiji.

Table 1. Severe Tropical Cyclones in Fiji, from (Revell 1981; Kerr 1976).

Tropical Cyclone	Date	Station	p_{min} (mbar)	V_{gust} (m s^{-1})
-	1965	Nadi	-	75 (est)
Bebe	Oct 1972	Nadi	945	-
-	Jan 1951	Suva	958	59
-	Feb 1941	Suva	965	52
Oscar	Mar 1983	Kadavu	953	72
Eric	Jan 1985	Nadi	961	52
Nigel	Jan 1985	Viwa	-	52
Raja	Dec 1986	Udu	-	50

p_{min} Minimum recorded pressure
V_{gust} Maximum recorded gust wind speed

Table 2. Details of wind data available for Fiji.

Source	Methods	Data Type	Station(s)	Data Period
Fiji Met Service (FMS)	GEVD; GPD	Annual maximum gust	Nadi	1948-1998, Missing [1952, 1961]
			Matuku	1971-1998
			Vunisea	1971-1998
			Nabouwalu	1955-1998, Missing [1974,1976-77]
			Suva	1944-1998, Missing [1948,1952,1974-75,1977-78]
	GPD; CMIS	Daily maximum gust	Nadi	01/01/1962-31/12/1998
			Suva	01/01/1979-31/12/1998
NIWA (NZ)	Vickery-Gomes; GPD	3 hourly mean wind speed (synops)	Nadi	01/01/1993-31/12/1998
			Matuku	01/01/1981-31/12/1998
			Vunisea	01/01/1979-31/12/1997
			Nabouwalu	01/01/1978-31/12/1998

This is Typ1 I GEVD sometimes called the Gumbel Distribution (Gumbel 1958). Details of the derivation of Equation (1) and GEVD Type II and Type III are given In Holmes and Moriarty (1999). In the above equations, u is the modal wind speed and $1/a$ is the scale parameter or dispersion. Taking natural logarithm of Equation (2) leads to the result:

$$V = u + \frac{1}{a}\{-\ln(-\ln(F_v(V)))\} \tag{3}$$

The above equation can be expressed in terms of a return period R, where $R = 1/P$, and P is the probability of exceedence of velocity V. For large return periods R:

$$V(R) = u + \frac{1}{a}\ln R \tag{4}$$

Gumbel (1958) has suggested a technique to obtain the values of variables u and $1/a$. An annual maximum wind speed sample size of at least 20 years should be ranked in order of increasing wind speed (m = 1 to N where N is the sample size). According to Gumbel (1958), the best probability level corresponding to the m^{th} observation turns out to be $P_m(<V) = m/(N+1)$. The ranked data and the associated probability ordinates (P_m) provide an empirical estimate of the parent distribution of annual maxima denoted by $F_v(v)$. Thus plotting V against -ln (-ln($m/(N+1)$)) yields the required parameters u and $1/a$.

Another method of obtaining the reduced variate $F_v(v)$ is the Dorman's method which is a modified Gumbel approach and which has been utilised in the AS1170.2-1989 (1989). In this approach a composite record of wind data produced by similar extreme wind sources is utilised instead of records from a single station. The AS1170.2-1989 has composited records in each of the four regions by ignoring the lowest 50 % of the data and the top four data points. This method also effectively increases the data length and is believed to subsequently improve the performance of the traditional Gumbel method. The Dorman method will be used as a reference for comparing the performance of different methods.

2.2 GENERALISED PARETO DISTRIBUTION (GPD)

The Generalised Pareto Distribution is given by:

$$F_y(y) = 1 - \left\{1 + \left(\frac{k\,y}{\sigma}\right)\right\}^{-1/k} \tag{5}$$

where σ is a scale factor and k is a shape factor. Like the GEVD, the GPD also has three possible cases determined by three possible values for the shape factor k. The case $k < 0$ is the usual Pareto distribution, which is physically unrealistic. When k is forced to be 0 it is equivalent to assuming a Type I GEVD or Gumbel distribution for the annual maxima. The proof of this is provided in Holmes and Moriarty (1999). The shape factor $k > 0$ is frequently used.

2.3 COOKS METHOD OF INDEPENDENT STORMS (CMIS)

Originally expounded by Cook (1985), the Method of Independent Storms (CMIS) is a more advanced form of the standard Gumbel (Type I GEVD) distribution. The data used in this analysis are all independent storm maxima and not just the annual maxima used in the conventional extreme value analysis method. For example, for the analysis of wind data for Fiji, all independent tropical cyclone maxima that occurred in a given year shall be extracted and used instead of a single maximum from that year. Since the storm maxima are independent (Harris 1999), it follows from orthodox extreme value theory that the distribution of the largest annual maximum out of r independent maxima per year, has a probability distribution given by:

$$F_q(q) = \{\exp(\exp(-a(q-x)))\}^r \tag{6}$$

where $q = V^2$ (with V as in Equation (2)) is used to transform the parent distribution closer to an exponential form in order to accelerate the convergence to the Fisher Tippett Type I asymptote; see Harris (1999).

2.4 VICKERY-GOMES METHOD (VG)

The Vickery-Gomes method uses a Poisson distribution with the wind speed population following a Weibull distribution and is given by:

$$P(<V) = \exp\{-1300\,(V/c)^{k-1}\exp(-(V/c)^k)\} \tag{7}$$

Equation (7) can be approximated by a Fisher-Tippett Type I distribution where the modal value u and the dispersion $1/a$ are obtained from:

$$u = c\,7^{1/k} \quad \text{and} \quad a = 7k/u \tag{8}$$

in which the parameters c and k are obtained from Equation (7). The values of u and a obtained above can be substituted in Equation (4) to obtain an R-year return wind speed.

3 DATA DESCRIPTION AND SUITABILITY OF EVA METHODS

The data used for extreme value analysis in the present study have been extracted from the archives of the Fiji Meteorological Services (FMS) and the National Institute for Water and Atmospheric Sciences in New Zealand (NIWA). Since the anemometers for all the five stations under study were located in standard exposures of 10m anemometer height in terrain category 2, there was no need for any corrections to the wind speeds. A detailed description of the data utilised in the analyses appears in Table 2. It shows that more than 20 years and up to 54 years of data are available for all the stations, with the exception of the mean wind speed data for Matuku.

The major statistical techniques of GEVD, GPD, CMIS and VG contain certain advantages and disadvantages. These properties in turn determine their reliability and suitability in determining return periods for Fiji. The preferred approach to determine design gust wind speeds has traditionally been the GEVD Type I, namely the Gumbel method. The prime advantage of this approach is that the observations employed are themselves extreme values, which are more useful than the total body of winds. However, a continuous record of wind speeds is necessary to determine the annual maxima. Typically, 20 years of data are needed to yield just 20 data points, with the bulk of the data being discarded. Fortunately, all the five stations that are being studied have at least 20 years of data (some as high as 49 years) which makes it feasible to apply this approach to the Fiji situation. However, a question that still remains is the ability of this method to reasonably estimate the ultimate limit wind speeds with return periods as high as 1000 years due to not having an upper limit in its estimates. This problem has been solved to some extent in AS1170.2-1989 by compositing data for stations within similar regions, thus simulating longer records for analysis. Up to 174 data points have been composited at maximum in regions in Australia (Holmes *et al*. 1990) to derive basic design wind speeds. This method is readily applicable to Fiji since ample data is available.

In the last decade a novel approach known as the 'peaks over threshold' was developed by Davison and Smith (1990) that offers the potential for more realistic estimates of the 'tails' of the GEVD Type III. This assumes the wind distribution being a Poisson process with the extreme values being represented by a GPD. The scheme can be used for any type of data set, provided it has a sufficiently high threshold. Thus one disadvantage being that for higher thresholds more data are discarded. Nevertheless, the significance of this scheme is that it could be used to represent tropical cyclone data well, by ensuring that the threshold is always above the maximum wind that could be produced by other weather systems (for example > 20 m/s). Furthermore, in the GPD approach all the data available above a particular threshold can be used instead of just the annual maxima as in GEVD III.

The Vickery-Gomes method is a form of Poisson and Weibull distributions. Some of its advantages are that a continuous record is not required and use can be made of discrete observations, such as 3-hourly surface observations, and short lengths of records enables adequate estimates of extreme wind speeds corresponding to average return periods as low as one week. The main disadvantage of the VG approach is that its success depends on the actual extreme wind speeds being members of the measured parent distribution. For tropical cyclone prone countries like Fiji, the extreme winds are as low as less than one percent of the total wind distribution in any years record. The ability of this technique to determine design gust wind speeds in countries affected by tropical cyclones is therefore questionable.

4 RESULTS

4.1 GUMBEL AND DORMAN'S ANALYSIS

The results obtained from Gumbel analysis of all the annual maximum gust data available for each of the five stations are presented in Table 3. It depicts that for N-year return period (where N = sample size), the Gumbel estimated wind speeds $V(R=N)$ for all 5 stations' are marginally close to the maximum observed gust wind speed V_{max}, as expected. However, it can be seen that the values of the predicted 1000-year return period V_u are between 37 to 58 percent higher than measured V_{max}. Thus it is quite justifiable to presume that in the lifetime of the structure, the probability of experiencing gust wind speeds higher than the Gumbel estimated V_u are extremely rare.

These results can be compared with those in Table 4 of Basher (1985) for stations Suva and Nadi, where a Gumbel analysis was conducted on limited Fiji wind data some decades ago. It is noted that Basher used 17 or 18 years of data. Nevertheless, there is almost exact agreement on V_{20} for Nadi, but for Suva, present analysis yields a much smaller V_{20} of 40 m/s as compared with 48 m/s. The present analysis is considered more reliable since it has more than twice the sample size of that of Basher.

Another interesting observation in Table 3 is the similarity between four stations: Nadi, Matuku, Vunisea and Nabouwalu, with Suva standing out as having lower recorded and predicted gust wind speeds. This correlates quite well with historical accounts of Suva sustaining much less damage during past tropical cyclones. The similarity between the four stations other than Suva expresses the need to assign a single design gust wind speed for these stations. Since the modes and dispersions do not deviate a lot from each other for these stations, a composite record could be compiled. The results of such a composite analysis, which is Dorman's analysis, is included in Table 5.

From Table 5, it could be deduced that reasonable values for ultimate limit states design gust wind speed and serviceability limit states design gust wind speed for all regions in Fiji except for the greater Suva region could be about 82 m/s and 50 m/s respectively. This is the procedure utilised as a guidance in the AS1170.2-1989 for obtaining design gust wind speeds in tropical cyclone region D of Australia. For Suva, since a composite analysis is not possible, the respective design gust speeds may be taken as 64 m/s and 40 m/s from the Gumbel analysis.

Table 3. Results of Gumbel analysis for Fiji.

Station	$V(R)$[a]	N[b]	V_N[c]	V_{max}[d]	% Difference between V_N and V_{max}	SLSWS[e] V_{20}[e]	ULSWS[f] V_{1000}[f]	% Difference between V_{max} and V_{1000}
Nadi	23.5 + 9.6 ln R	49	61	57	-7%	52	90	+58%
Matuku	19.6 + 10.1ln R	29	54	57	+5%	49	89	+57%
Vunisea	18.8 + 9.6 ln R	27	51	56	+10%	21	85	+51%
Nabouwalu	18.7 + 9.2 ln R	41	53	57	+6%	46	82	+45%
Suva	42.3 + 11.9 ln R	46	45	47	+3%	40	64	+37%

[a]$V(R)$ = Design Gust Wind Speed Equation
[b]N = Sample size (In this case equivalent to number of years of available data)
[c]V_N = Gumbel estimated N-yr gust wind speed
[d]V_{max} = Maximum observed wind speed.
[e]SLSWS = Gumbel estimated 20-yr return wind speed V_{20} for serviceability state V_s
[f]ULSWS = Gumbel estimated 1000-yr return wind speed V_{1000} for ultimate limit state V_u

Table 4. Gumbel estimates in m s^{-1}, from Basher (1985).

Station	N[a]	V_2	V_5	V_{10}	V_{20}	V_{50}	V_{100}	V_{max}
Suva	17	27	36	43	48	56	62	57
Nadi	18	27	38	45	52	61	67	57

N = number of years of data
V_i = i year Gumbel estimate

Table 5. Results of Dorman's (AS1170.2-1989 1989; Gumbel 1958) composite analysis for the four similar stations other than Suva.

Technique	V(R)	V_{20}	V_{1000}
Dorman [2, 7]	26.2 + 8.1 ln R	50	82

Table 6. Results of Cooks Method of Independent Storms.

Station		$V(R)$	N	r	R'^2	Return Period R								
						20	50	100	200	500	1000	2000	5000	10000
Nadi	A	$\sqrt{(646+625 \ln R)}$	44	1.16	0.93	50.2	55.6	59.4	62.9	67.3	70.4	73.5	77.3	80.0
	B	$\sqrt{(712 + 625 \ln R)}$	27	1.29	0.93	50.8	56.2	59.9	63.4	67.8	70.9	73.9	77.7	80.4
Suva		$\sqrt{(465+435 \ln R)}$	27	1.29	0.89	42.0	46.5	49.7	52.6	56.3	58.9	61.4	64.6	66.9

N = Number of data (equivalent to number of tropical cyclones)
r = Storm rate (number of tropical cyclones versus years of data)
R'^2 = Regression coefficient

Table 7. Results of Mean Excess over Thresholds for station Nadi (Type III – $k > 0$).

Threshold (m/s)	Number of Exceedance	λ	σ	k	R'^2	Return Period								
						20	50	100	200	500	1000	2000	5000	10000
20	74	1.95	9.80	0.12	0.09	48.9	54.3	58.0	61.4	65.5	68.3	70.8	73.9	76.0
24	33	0.87	14.62	0.32	0.36	51.4	56.0	58.8	60.9	63.2	64.5	65.5	66.6	67.2
28	16	0.42	22.30	0.69	0.87	52.8	56.2	57.7	58.6	59.3	59.6	59.8	59.9	60.0
32	10	0.26	24.61	0.86	0.93	53.8	57.5	58.9	59.7	60.2	60.4	60.5	60.6	60.6
36	9	0.24	15.57	0.64	0.89	51.4	55.4	57.2	58.4	59.3	59.7	60.0	60.2	60.3
40	8	0.21	10.79	0.48	0.83	51.2	55.2	57.3	58.8	60.1	60.8	61.3	61.7	61.9
44	5	0.13	9.49	0.53	0.77	51.2	55.3	57.3	58.7	59.9	60.5	60.9	61.3	61.5

4.2 ANALYSIS USING COOKS METHOD OF INDEPENDENT STORMS (CMID)

The CMID method is believed to be an improvement over the Gumbel but as shown in Table 6, the convergence is quite high meaning the predicted wind speeds would under-estimate the design gust wind speed. A V_{1000} value of 71m/s for Nadi, for example, is slightly lower than the maximum value of wind speed recorded so far (see Table 1) for this station. Furthermore, when compared with the reference Dorman's analysis results for Nadi, V_{20} values (50 and 52 m s^{-1}) are similar. However, V_{1000} = 71 m s^{-1} from CMID as compared with 82 m s^{-1} from Dorman appears to confirm that the CMID is perhaps non-conservative.

Table 8. Ultimate limit states basic design gust wind speeds (m/s) predicted by different methods.

Station	Extreme Value Analysis Technique					
	Gumbel	Dorman's	GPD Type I	GPD Type III	CMIS	VG
Nadi	90	82	70	60	71	44
Suva	64	64	61	52	59	-
Matuku	89	82	-	-	-	45
Nabouwalu	82	82	-	-	-	77
Vunisea	85	82	-	-	-	66

Table 9. Current and recommended basic design gust wind speeds for Fiji.

Region	Type	Current (m s^{-1})	Recommended (m s^{-1})
[1] Suva and eastern coasts of Viti Levu	ultimate	70	65
	serviceability	45	40
[2] Elsewhere in Fiji	ultimate	70	82
	serviceability	45	50

4.3 GENERALISED PARETO DISTRIBUTION (GPD) ANALYSIS

The Generalised Pareto Distribution which assumes wind distribution to be a Poisson process is known to estimate the 'tails' quite well. Table 7 shows that a threshold of 32 m s^{-1} was chosen for the GPD analysis, since it has the highest regression coefficient R^2 out of all the other thresholds (see also Harris (1999)).

The authors express reservations in using the GPD model for Fiji. This is due to the fact that majority of the anemometers are destroyed in high winds resulting in the estimation of the exceedance rate λ being always lower than its true value. Furthermore, V_u values of 60 m s^{-1} and 70 m s^{-1} for GPD Type III and Type I (not shown here) respectively are lower than the maximum observed wind speeds in Table 1. A careful observation shows that these low predictions could be attributed to unrealistic values for k obtained due to small number of exceedances for thresholds, particularly for those larger than 28 m s^{-1}. Consequently, the parameters obtained for a best line fit are not reasonable.

5 DISCUSSION

The ultimate limit states basic design gust wind speeds obtained from the various extreme value analysis methods are shown in Table 8. If the results from the Dorman's method are taken as reference, then the GPD, CMIS and VG methods are seen to be highly under-predicting the ultimate limit basic design gust wind speed. The predictions of GPD Type I and Type III as well as CMIS are between 12 to 24% lower whereas for VG, it is 46% lower as compared with that from Dorman's method. This is true for stations Nadi, Matuku, Nabouwalu and Vunisea that are in the severely affected tropical cyclone regions of Fiji. However, for less severely affected regions like Suva that lie in the eastern parts of Viti Levu, the predictions are 5-21 % lower from the GPD Type I and III and CMIS methods. This confirms that the techniques of GPD, CMIS and VG perform quite poorly in predicting basic design gust wind speeds for severe tropical cyclone affected regions in comparison with performance in areas impacted by less severe tropical cyclones. The poor performance of the GPD method is probably due to the scarcity in available data, in particular when the threshold is set at 28 m s^{-1} or more.

Table 8 also shows that the results from Gumbel and Dorman's methods indicate similarity between predicted wind speeds for the four stations: Nadi, Matuku, Vunisea and Nabouwalu (that lie in the severe tropical cyclone region) and expresses the need to assign a single design gust wind speed for these stations. On the other hand, there is suggestion that a slightly lower design gust wind speed for Suva should be used. Table 9 summarises the current wind speed provisions of the Fiji Building Code, together with recommendations from the present study.

6 CONCLUSIONS

The study shows that the Cooks Method of Independent Storms and Vickery Gomes method perform poorly in a region affected by severe tropical cyclones. In the case of Fiji, predictions from these methods were between 12% to 46% lower than that obtained by Dorman's method. Furthermore, based upon the results of Dorman's analysis, the study recommends that the National Building Code of Fiji adopt AS1170.2-1989 (now AS/NZS1170.2 2002) Region C provisions for Suva and eastern Viti Levu only, while AS1170.2-1989 Region D provisions for elsewhere in Fiji. The present provision for the use of Australian Region C wind data for all of Fiji is inadequate as it under-estimates design gust wind speeds, particularly for regions other than Suva. The differences between the present results and data for Australian Region C are attributed to the greater frequency of tropical cyclones affecting Fiji. It is recommended that in the future, Monte Carlo simulation techniques be applied to confirm and perhaps improve the data generated in the present study.

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