

# Development of Flood Monitoring Index for Daily Flood Risk Evaluation: case studies in Fiji

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## Abstract

Both fluvial and pluvial floods are a common occurrence in Fiji, with the fluvial floods causing significant economic consequences for this island nation. To investigate flood risk on a daily basis, the Flood Index ( $I_F$ ) is developed in this study, based on the rationale that the onset and the severity of a flood event on any given day is based on the current and the antecedent day's precipitations. The mathematical methodology considers the notion that the impact of daily cumulative precipitation on a particular flood event arising from a previous day's precipitation, which decreases gradually over time due to the interaction of hydrological factors (e.g., evaporation, percolation, seepage, surface run-off, drainage, etc.). These are accounted for, mathematically, by a time-reduction weighted precipitation influencing the magnitude of  $I_F$  with the gradual passage of time. Considering the duration, severity and intensity of all identified flood events, the applicability of daily  $I_F$  is tested at 9 study sites in Fiji using a 30-year precipitation dataset (1990 to 2019) obtained from Fiji Meteorological Services. The newly developed  $I_F$  is also applied at several flood prone sites, with results demonstrating flood events were common throughout the country, mostly notable between the months of November to April (the wet season). Upon examining changes in daily  $I_F$ , the subsequent flood properties were determined, showing that most severe events generally start in January. The flood event with the highest severity was recorded in Lautoka ( $I_F^{acc}(\text{Flood Severity}) \approx 149.14$ ,  $I_F^{max}(\text{Peak$

Danger)  $\approx 3.39$ ,  $D_F$ (Duration of Flood)  $\approx 151$  days,  $t_{onset}$ (Onset Date) = 23rd January 2012 ) , followed by Savusavu ( $I_F^{acc} \approx 141.65, I_F^{max} \approx 1.75, D_F \approx 195$  days,  $t_{onset} = 27th$  November 1999) and Ba ( $I_F^{acc} \approx 131.57, I_F^{max} \approx 3.13, D_F \approx 113$  days,  $t_{onset} = 9th$  January 2009). These results clearly illustrate the practicality of daily  $I_F$  in determining the duration, severity, and the intensity of flood situations in Fiji, as well as its potential application to small island nations. The use of daily  $I_F$  to quantify the flood events can therefore enable a cost-effective and innovative solution to study historical floods in developing and first world countries with methodology being particularly useful to their governments, private organizations, non-governmental organizations and individual communities to help develop more community-amicable policy and strategic plans for flood impact preparation and its risk mitigation.

**Keywords:** Flood Monitoring; Flood Index; Risk Mitigation.

### Acronyms

AWRI	Available Water Resource Index
$D_F$	Duration of Flood
FJD	Fijian Dollar
GDP	Gross Domestic Product
$I_F$	Flood Index
$I_F^{acc}$	Flood Severity
$I_F^{max}$	Peak Danger
$P$	Precipitation
$P_E$	Effective Precipitation
SPCZ	South Pacific Convergence Zone
SPI	Standardized Precipitation Index
SWAP	Standardized Weighted Average of Precipitation
WAP	Weighted Average of Precipitation

## 1 Introduction

Floods are a common occurrence in most parts of the globe. More than two billion people were affected by floods between 1998 and 2017 (Wallemacq & House 2018). Adding on, floods resulted in 142,088 deaths and amounted to a total of 656 billion USD in economic losses for the 20-year period. In contrast to first world countries, the effects of such disasters are more

devastating in developing countries (Keoduangsine et al. 2014). Fiji, which is a developing country has faced some of the severest floods in the past. One of the worst disasters that the country faced was the 1931 hurricane and flood in which at least 225 people lost their lives (Yeo & Blong 2010). It is estimated that the damage caused by the January 2012 floods totalled around 48.6 million FJD for the Ba and Penang river catchments combined (Brown et al. 2016). These are significant losses for a country with a GDP of less than 6 billion USD (The World Bank Group 2019) and a population of less than a million. According to Brown et al. (2016), floods will be more frequent and severe in the future, resulting in increasing annual losses due to climate change. Therefore, this brings up the need to develop and apply innovative and cost-effective solutions that can assist to mitigate the impacts caused by floods in developing countries such as Fiji.

Subsequently, scientific tools with practical applications in the 21<sup>st</sup> century are necessary considering the current trends of water resources (Yevjevich 1991). Over the years, there have been many flood monitoring methods that have been used to quantify flood events including the Standardized Precipitation Index (SPI) (Seiler et al. 2002), Weighted Average of Precipitation (WAP) (Lu 2009) and the Flood Index ( $I_F$ ) (Deo et al. 2015). These methods have been used to monitor floods at different places around the globe and have been accepted as suitable tools for flood monitoring. Such quantification of floods assists in understanding more about these floods and helps in better decision making in the future. Consequently, using historical precipitation data for the flood prone areas in Fiji, flood monitoring indices could be used to examine the duration, severity and intensity of flood events that have occurred in these areas, in the past. Yet, a key drawback of these widely used methods for flood analysis and monitoring is that they largely rely on total rainfall data therefore its practicality needs to be investigated before implementation.

The SPI (McKee et al. 1993) was initially developed for drought assessments but many studies have used it for monitoring floods (Seiler et al. 2002; Guerreiro et al. 2008; Wang & Cao 2011). SPI makes use of historical precipitation data to determine if a year is a flood or drought year for that area. However, monitoring floods and droughts for a short timescale is not possible using SPI because it does not consider the previous day's precipitation. For instance, if there was no rainfall for a short period (for example, less than a week), the index will classify the period as a drought even if there was heavy precipitation on the days which led to a flood prior to that short period. Therefore, due to the inability of SPI to monitor flood situations for short timescales, the daily monitoring of the start, duration and strength of floods, which is required

for this study, is not possible using SPI (Lu 2009). In addition, SPI does not consider other factors such as percolation, evaporation and surface run-off which are critical hydrological conditions to be considered when monitoring floods.

The fluctuations of remaining volumes of water due to heavy precipitation over time should be considered for assessing the possibility of floods (Ma et al. 2014). The extent of a flood is based on the current day and antecedent days' precipitation whereby the impact from the previous day's precipitation gradually decreases due to factors such as evapotranspiration, percolation, groundwater flow and surface runoff (Lu 2009). Two of the monitoring indices which account for the previous days precipitation are the WAP (Lu 2009) and  $I_F$  (Deo et al. 2015). Both WAP and  $I_F$  can be used for monitoring floods on shorter time scales (example daily) and considers other hydrological conditions such as evaporation and surface run-off, which is not accounted for by SPI (Lu 2009). Consequently, in terms of evaluating flood properties at short timescales based on rainfall, WAP and  $I_F$  appears to be a better option when compared with the commonly used SPI.

$I_F$  is a standardized metric which makes use of Effective Precipitation ( $P_E$ ).  $P_E$  is deduced from daily rainfall by placing emphasis on recent precipitation, based on a time-dependent reduction function (Byun & Chung 1998; Deo et al. 2014). When compared with WAP and its standardized version, SWAP (Lu et al. 2013),  $I_F$  has been more widely applied at various places around the globe to determine the duration, severity and intensity of flood events at short timescales (Nosrati et al. 2010; Deo et al. 2014; Deo et al. 2015; Deo et al. 2018). Also, unlike WAP, the computation of  $I_F$  also does not require parameters that needs to be chosen empirically (Lu 2009). As  $I_F$  has been more widely applied and tested when compared to WAP and its due to its ability to monitor flood events on a daily basis while accounting for various hydrological factors,  $I_F$  was selected as the suitable flood monitoring tool to be used in this research.

SPI has been the tool that has been generally used for analysis of rainfall and floods in Fiji (Nawai et al. 2015; Fiji Meteorological Service 2018). Therefore, an index which considers previous days' precipitation and other hydrological factors has not been used to monitor floods in the country till date. Therefore, using  $I_F$  to quantify floods will be an innovative and highly accurate method to determine the duration, severity, and intensity of previous flood events in Fiji Islands. This study is expected to provide results that can be used to analyse past floods in the country and potentially allow for better flood related decision making in the future.

The main objectives of this paper are threefold:

- i. To compute Effective Precipitation ( $P_E$ ), and successively determine Available Water Resource Index (AWRI) and Flood Index ( $I_F$ ).
- ii. To apply  $I_F$  at various study sites in the Fiji Islands.
- iii. To investigate the duration, severity and intensity of flood events that have occurred at the study sites from 1991 to 2019.

Moving forward, the paper is structured as follows. Firstly, the study area and the characteristics of the rainfall data obtained for the computations will be discussed. Then, the methods used in computing the  $I_F$  will be specified. After this, the results will be presented and discussed. Finally, the conclusion will report the key insights from the results and state the usefulness of  $I_F$  as a tool for monitoring flood events.

## **2 Materials and Methods**

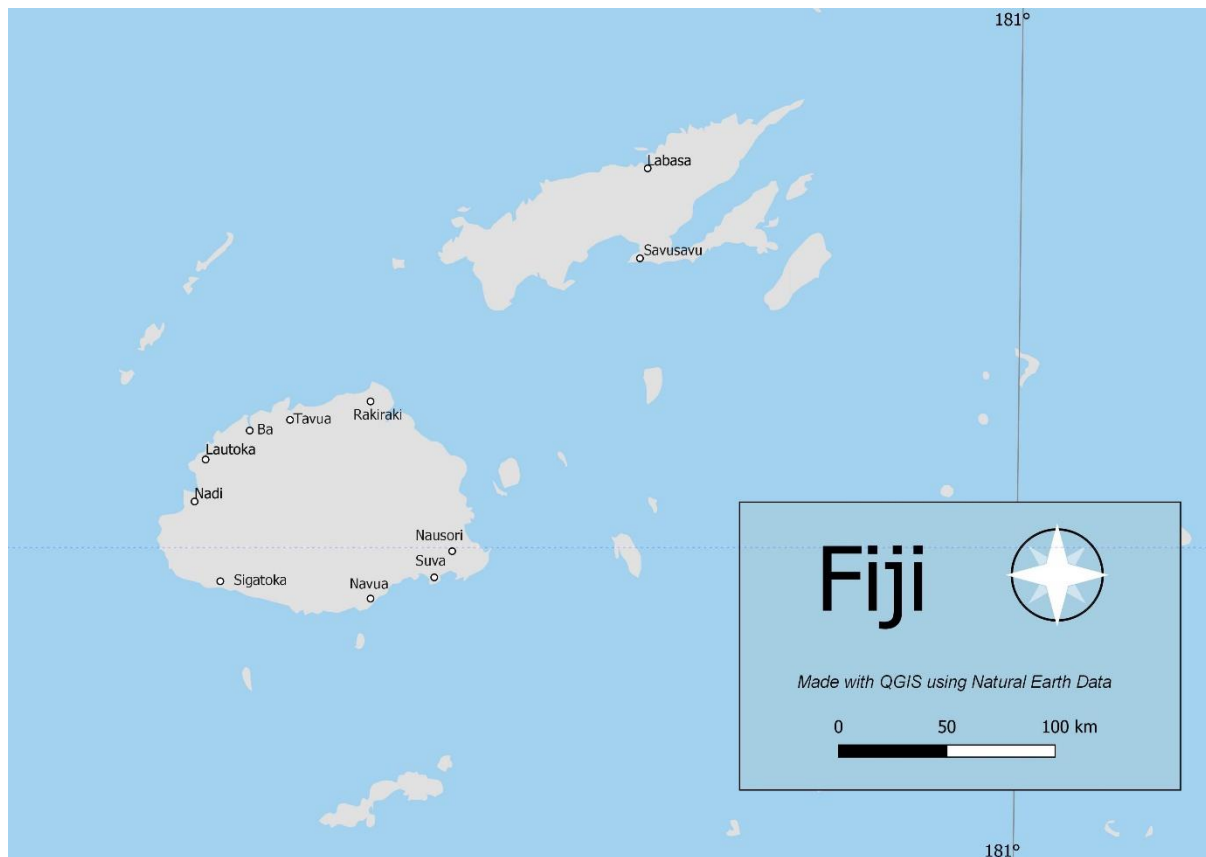
### **2.1 Study Area**

This paper has been focused on the Fiji Islands. The group of islands are in the south-west Pacific Ocean and has an oceanic tropical climate. The location of the South Pacific Convergence Zone (SPCZ) has a great influence on Fiji's rainfall and climate (Feresi et al. 2000). The country experiences higher than expected rainfall during the La Niña years and this leads to regular flooding, particularly through the wet season (Fiji Meteorological Service 2018). The Fiji group consists of more than 300 islands spread over 1.3 million square kilometres of the South Pacific Ocean (Feresi et al. 2000). Multiple areas from the two largest islands (Viti Levu and Vanua Levu) have been covered in this paper. 87% of the total land area is covered by these two islands (Feresi et al. 2000). As the study region is small and floods are common in most parts, it was possible to cover most major towns and cities of the country during this research. Figure 1 shows the map of the study area and labels the respective sites.

### **2.2 Dataset**

The daily rainfall data for Labasa, Savusavu, Rakiraki, Tavua, Lautoka, Nadi, Ba, Navua, Suva, Nausori and Sigatoka from January 1990 to December 2019 (30 Years) was successfully obtained from the Fiji Meteorological Service. Table 1 summarizes the relevant metadata of rainfall dataset and the respective study sites. The calendar means imputation method was used to fill-in the missing data. The standard data period used in the computations was from 1st January 1990 to 31st December 2019. However,  $I_F$  was calculated from 1991 as antecedent

precipitation of 365 days was required in the calculations. Furthermore, to accommodate for leap years (366 days), the rainfall amount for February 29th was added to March 1st. Two sites, Tavua and Navua, were excluded from further analysis because data was not available for the entire period and that could have affected the comparison results.



**Figure 1** – A map of Fiji showing the different study sites

**Table 1** - Characteristics of the raw dataset for the different study sites (Source: Fiji Meteorological Services).

Site Name (A-Z)	Location	Data Range	Missing Data (%)	Average Recorded <i>P</i> (mm)	Maximum Recorded <i>P</i> (mm)
Ba	17.53°S, 177.66°E	(01/01/1990, 31/12/2019)	1.15	6.23	500.00
Labasa	16.43°S, 179.36°E	(01/01/1990, 31/12/2019)	2.36	5.94	272.40
Lautoka	17.62°S, 177.45°E	(01/01/1990, 31/12/2019)	1.46	5.44	390.60
Nadi	17.78°S, 177.44°E	(01/01/1990, 29/02/2020)	0.02	5.43	356.20

Navua	18.22°S, 178.17°E	(01/01/1992, 01/12/2019)	6.35	9.75	255.00
Nausori	18.03°S, 178.56°E	(01/01/1990, 29/02/2020)	0.24	8.02	260.00
Rakiraki	17.39°S, 178.07°E	(01/01/1990, 31/12/2019)	0.23	6.29	450.40
Savusavu	16.78°S, 179.34°E	(01/01/1990, 31/01/2020)	1.08	5.64	243.00
Sigatoka	18.14°S, 177.51°E	(01/01/1990, 30/11/2019)	5.34	4.79	183.00
Suva	18.13°S, 178.45°E	(01/01/1990, 29/02/2020)	0.12	8.17	272.00
Tavua	17.44°S, 177.86°E	(01/01/1990, 31/03/2009)	19.25	4.99	404.60

### 2.3 Flood Index Computation

MATLAB (MathWorks 2019) was chosen as the software package to develop the flood index and perform the relevant computations in this study.

The following steps were taken to obtain the  $I_F$ . The first step was to calculate the Effective Precipitation ( $P_E$ ).  $P_E$  is determined using a time-dependent reduction function and is the sum of the precipitation for current and antecedent days (Byun & Chung 1998). In the calculation of the  $P_E$  for a particular day, the precipitation of the antecedent days is also considered, but with reduced weights. Therefore, if 365 days prior precipitation is to be considered, the influence of precipitation from 1 day prior would be 100%, for two days prior would be 85%, 77% for three days prior and eventually approximately 0.0423% for the precipitation that occurred 365 days prior (Deo et al. 2018). This is inline with the rationale of Lu (2009) which states that due to conditions such as evaporation, seepage, and runoff, the influence of previous days precipitation on current days water balance gradually decays. Therefore, as this mathematical model accounts for the daily depletion of water due to various hydrological conditions, it assists in the accurate monitoring of flood situations. The current day's  $P_E$  is determined using the following equation:

$$P_{E_i} = \sum_{N=1}^D \left[ \frac{\sum_{m=1}^N P_m}{N} \right] \quad (1 \leq m \leq 365) \quad (1)$$

where  $P_m$  is the recorded rainfall for any day,  $m$  and  $N$  is the duration of the antecedent period (365 days).

After the  $P_E$  was calculated, the AWRI value was obtained. AWRI is the combined precipitation ( $P$ ) over an annual cycle and used weight ( $W$ ) (Byun & Lee 2002). As presented in Eq (2), the mathematical equation for obtaining the AWRI is simpler than rainfall-runoff models and this makes it more advantageous in the assessment of water reserve balances (Deo et al. 2018). Generally, a larger magnitude of AWRI that is higher than the normal implies a surplus of water resources and the likelihood of a flood situation (Han & Byun 2006).

$$AWRI = \frac{P_E}{W} \quad (2)$$

$$W = \sum_{n=1}^{n=D} \frac{1}{n} \quad (3)$$

where  $D$  is the duration of the antecedent period (365 days) and  $n$  will range from 1 to  $D$  (365)

Flood Index ( $I_F$ ) is the normalized version of  $P_E$ . If  $I_F$  for a day is greater than zero ( $I_F > 0$ ), it is generally regarded as a flood situation. However, the criteria to classify a flood situation can be changed. This is because  $I_F > 0$ , can include flood events which have insignificant impacts. Therefore, to account only for the significant floods, the classification measure needs to be adjusted. For instance, to only account for extreme floods,  $I_F > 2$  can be the benchmark to classify a flood situation. Table 2 shows the different categories for classification of floods that can be used. These classification categories are based on earlier studies of Deo et al. (2015). This flexible criterion makes  $I_F$  advantageous over using raw values of  $P_E$  or AWRI in determining a flood situation. In Eq(4), which shows the mathematical formula of obtaining the  $I_F$ ,  $\frac{2019\overline{P_E^{max}}}{1991\overline{P_E^{max}}}$  and  $\sigma(\frac{2019\overline{P_E^{max}}}{1991\overline{P_E^{max}}})$  are the means and standard deviations of yearly maximum daily effective precipitation for the 1991-2019 period.

$$I_F = \frac{P_E - \frac{2019\overline{P_E^{max}}}{1991\overline{P_E^{max}}}}{\sigma(\frac{2019\overline{P_E^{max}}}{1991\overline{P_E^{max}}})} \quad (4)$$

**Table 2** - Classification of Severity of Flood based on the value of  $I_F$

Flood Index Measure	Severity Category
$I_F \leq 0$	Very Low (Drought)
$I_F > 0$	Low
$I_F \geq 1$	Moderate
$I_F \geq 1.5$	Severe
$I_F \geq 2$	Extreme



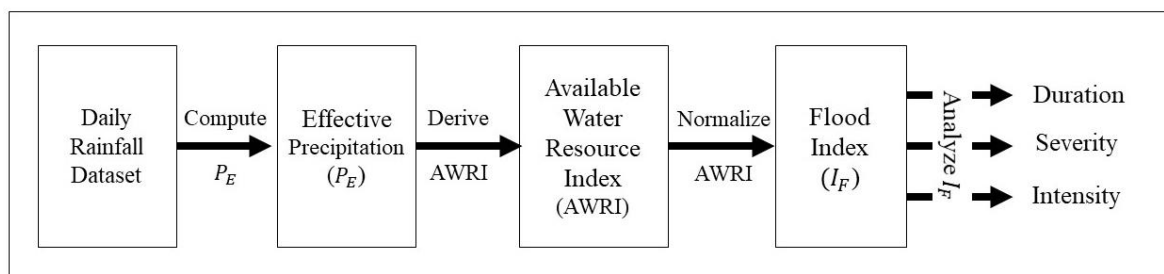
In accordance with the running-sum methodology by Yevjevich (1967), the following mathematical approaches to derive the severity, duration and intensity of flood situations from computed values of  $I_F$  was presented by Deo et al. (2015). The severity of the flood ( $I_F^{acc}$ ) is the sum of positive  $I_F$  from the first day of the flood situation ( $t_{onset}$ ), until the last day ( $t_{end}$ ). The duration of flood ( $D_F$ ) are the number of days between the start and end dates of the flood situation. The flood intensity ( $I_F^{max}$ ), which is the peak danger during the flood situation is the maximum  $I_F$  during the flood period. Eq (5-7) presents the mathematical equations to calculate these metrics. When computing the these metrics, the first and the last day of the flood situation can be adjusted based on the severity levels in Table 2.

$$I_F^{acc} = \sum_{t=t_{onset}}^{t=t_{end}} I_{F_i} \text{ where } I_{F_i} > 0 \quad (5)$$

$$D_F = t_{end} - t_{onset} \text{ (days)} \quad (6)$$

$$I_F^{max} = \max(I_F)_{t_{onset}-t_{end}} \quad (7)$$

The process of obtaining the  $I_F$  is illustrated in Figure 2. Furthermore, the results shown in Figure 3 for one of the sites demonstrates the practicality of using the  $I_F$  in computing the different flood properties.



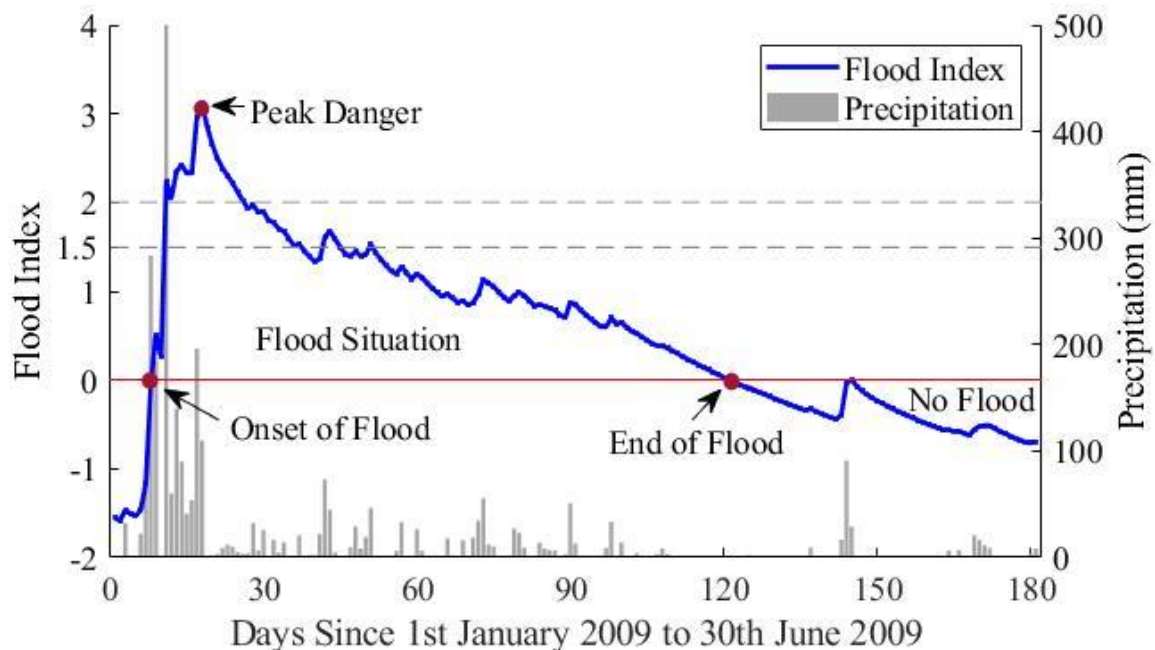
**Figure 2** – Process of Obtaining the Daily Flood Index

### 3 Results and Discussion

The practicality of the daily  $I_F$  is graphically evaluated as in Figure 3. Accordingly, the flood events that occurred from the 8<sup>th</sup> to the 16<sup>th</sup> of January 2009 were quantified (Office of the

Prime Minister 2009). This was initially done for the location, Ba as it was one of the highly impacted sites. The results obtained with the benchmark for a flood situation being  $I_F > 0$ , shows that the onset of the flood was the 9<sup>th</sup> of January and the end was the 1<sup>st</sup> of May, totalling a duration of 113 days and severity of 131.57, with the peak danger being 3.13. However, even though the area was in flood situation for 113 days, the impact of the flood situation was severe for 27 days, from the 11<sup>th</sup> of January to the 6<sup>th</sup> of February. Adding on, the severity of the flood was extreme only for 16 days from 11<sup>th</sup> to the 26<sup>th</sup> of January. These results showed the practicality of the  $I_F$  in determining the duration, severity and intensity of flood situations and its ability to categorize the severity of flood situations.

The flood situation for the other eight sites for the same period (first 180 days of 2009) was then determined. As shown in Figure 4, the duration, severity, and intensity of the floods in all these sites were different. This showed that even though the study area is small with most study sites being close by, there is a need to study the flood situation in all these areas separately. An analysis of the results illustrates that floods which started in January 2009 were only severe in the western side of the main island (Viti Levu) of Fiji (Ba ( $I_F^{acc} \approx 131.57$ ), Rakiraki ( $I_F^{acc} \approx 33.22$ ), Lautoka ( $I_F^{acc} \approx 35.87$ ), Nadi ( $I_F^{acc} \approx 35.85$ ) and Sigatoka ( $I_F^{acc} \approx 128.59$ )). The northern areas of the second main island (Vanua Levu) (Labasa ( $I_F^{acc} \approx 6.91$ ) and Savusavu ( $I_F^{acc} \approx 6.76$ )) had low severity while the severity in the central division (Nausori (*No Floods*) and Suva ( $I_F^{acc} \approx 0.03$ )) was very low. Adding on, only the floods in Ba and Sigatoka reached extreme peak severity. The floods in other areas of the western division reached severe peak danger.

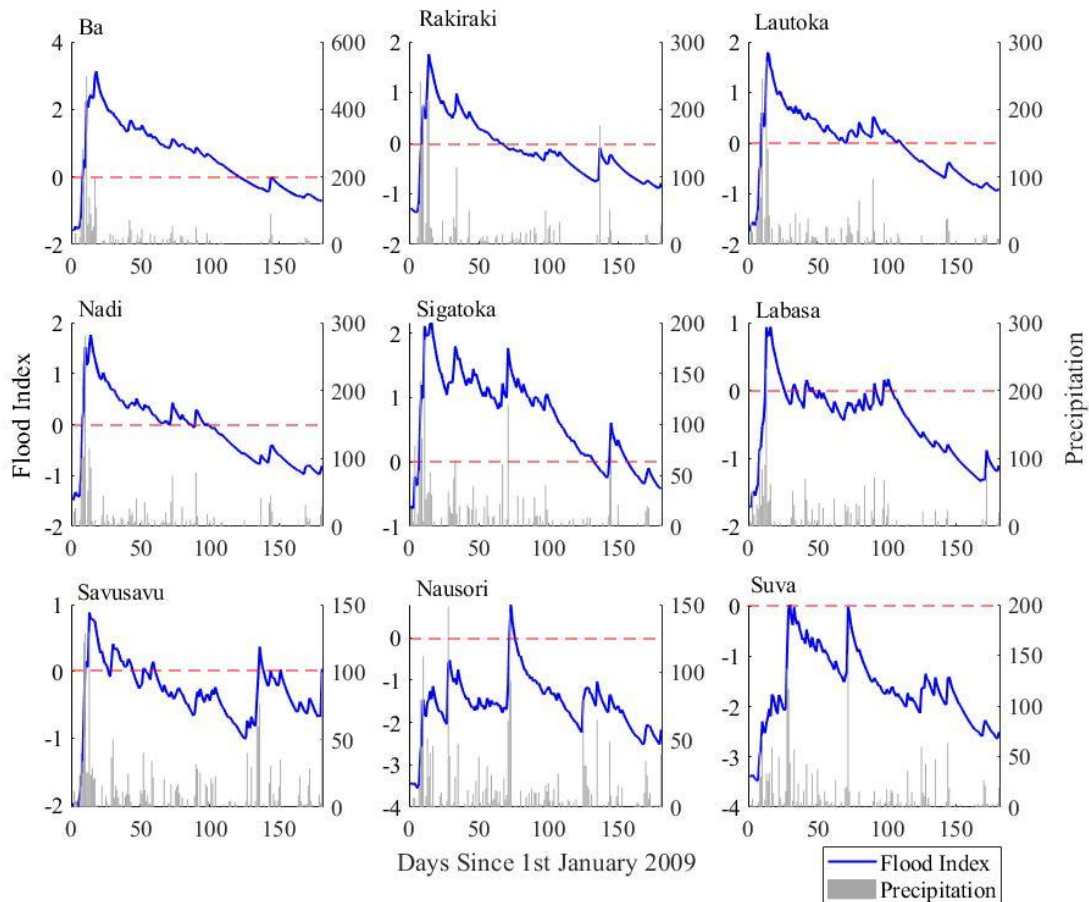


**Figure 3** - Flood Index applied to 2009 Floods in Ba. It shows how the index is used to determine the duration, severity, and intensity of floods.

The frequency of flood events during the 29-year period differed slightly for the nine sites. Figure 5 shows this distribution. The frequency of flood situations with different severity levels is also compared in this graph. It shows that even though there are many flood situations, only a handful of them are severe. For instance, Suva recorded 38 flood events during the study period but only 2 of them were severe. Labasa and Lautoka recorded 45 and 42 flood situations, respectively. Out of these, there was only one severe flood situation in Labasa and only two in Lautoka. Furthermore, when considering total number of flood situations for all study sites, out of the 352 flood situations, there were only 8 events during the 29-year period that reached extreme severity and 32 reached severe severity.

Most tropical cyclones and hurricanes in Fiji occur between December and April. These events sometimes also take place in October, November and May (Campbell 1984). Floods are more likely to occur during this period as well. This is shown in Figure 6, which illustrates that most of the severe flood situations started between January and May. As the highest number of floods had started in the first few months of the year, this shows the need for effective flood risk mitigation strategies to be implemented for these months. On the other hand, no severe flood events were recorded to have started between June and December and no floods started

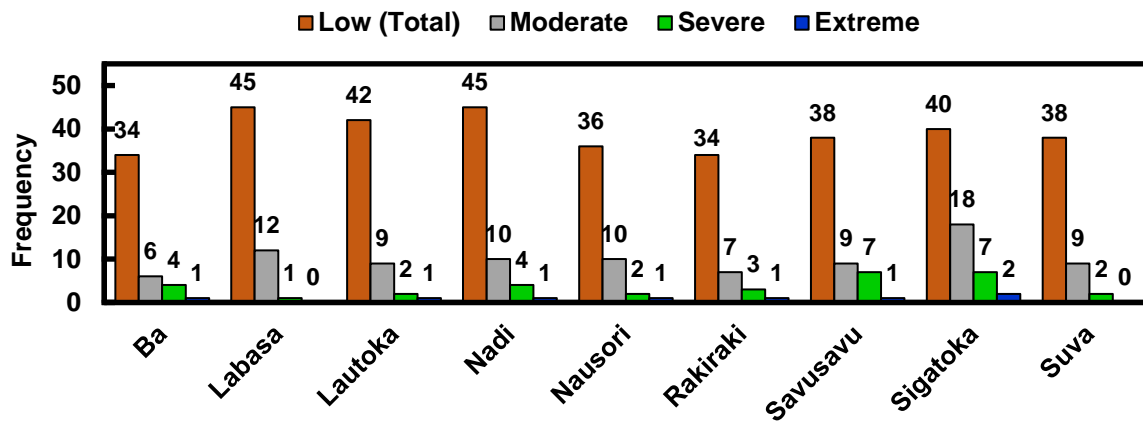
in August and September during the study period. The flood preparation strategies for the next wet season can potentially be developed during these months as there is a low probability that resources will need to be diverted for flood damage rehabilitation during this period.



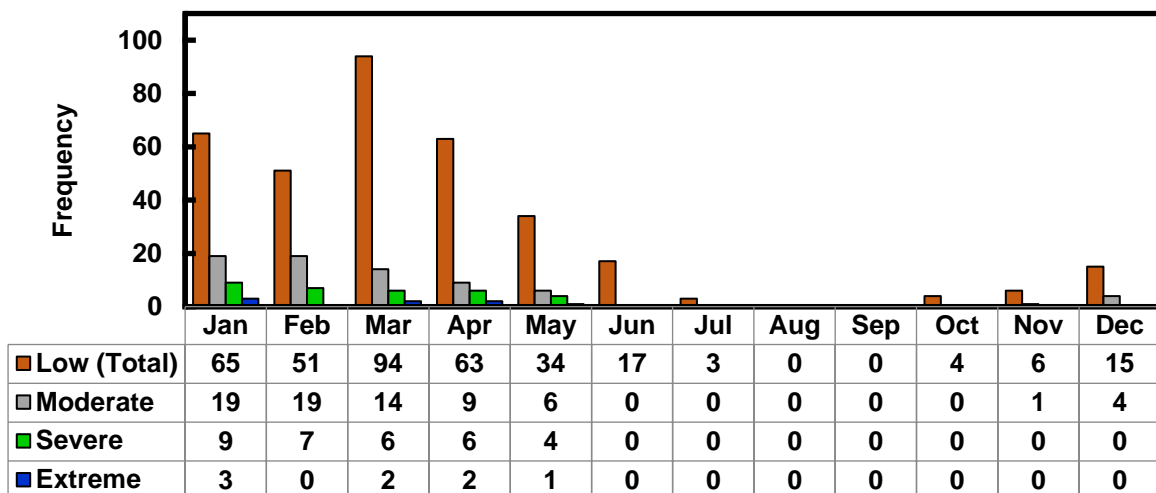
**Figure 4** - Flood Index monitored for different parts of Fiji from 1st January 2009 to 30th June 2009 (180 Days)

Based on Figure 7, the severity of floods which started from November to April is also quite high when compared to the other months of the year. It is interesting to note that the severity of flood events which commenced in January ( $I_F^{acc} \approx 1277$ ) is higher than the combined severity of flood events starting in the other months ( $I_F^{acc} \approx 1130.79$ ). Furthermore, the combined severity of floods starting in months apart from November to April period is very low ( $I_F^{acc} \approx 66.12$ ). Figure 8 presents the combined flood severity for each year during the 29-year period. Significant severity in floods were seen in 1997, 2000, 2002, 2014, 2017, 2018 and 2019. However, floods were most severe in 1999, 2008, 2009 and 2012.

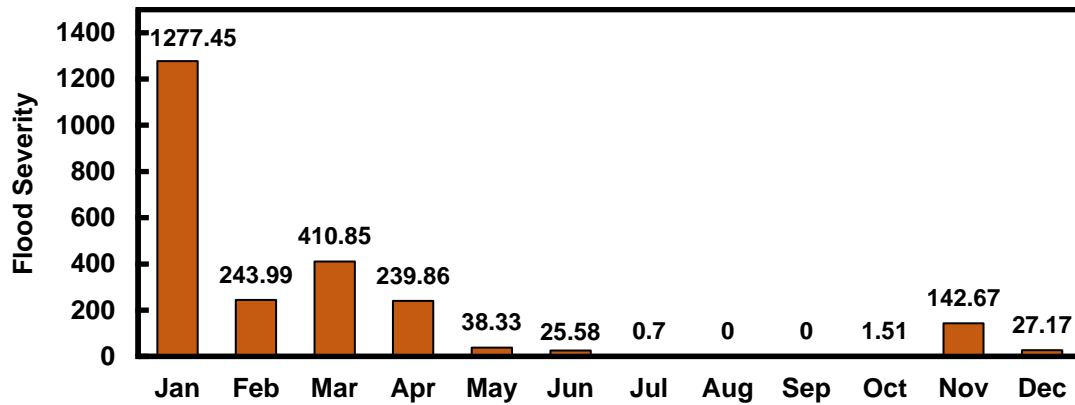
The peak severities as demonstrated in Figure 9 shows that the floods starting from January till April reach higher peaks when compared to other months. It is observed from the graph that the highest peak was reached in the month of January ( $I_F^{max} \approx 3.39$ ). This is followed by March ( $I_F^{max} \approx 3.21$ ) and April ( $I_F^{max} \approx 2.55$ ). The amount of rainfall during flood situations is also highest during these months. This trend is depicted in Figure 10. It shows the total amount of rainfall during flood events per month and the maximum amount of rainfall during a flood situation that started during that month. The floods which started in January had a total of 36725 mm of rainfall. This is followed by flood situations starting in March and April, which experienced a total of 18542 mm and 11536 mm of rainfall, respectively. The maximum amount of rainfall for a flood situation was recorded for a flood event which started in January (2504 mm). This measure was also followed by March (994.2 mm) and April (692 mm).



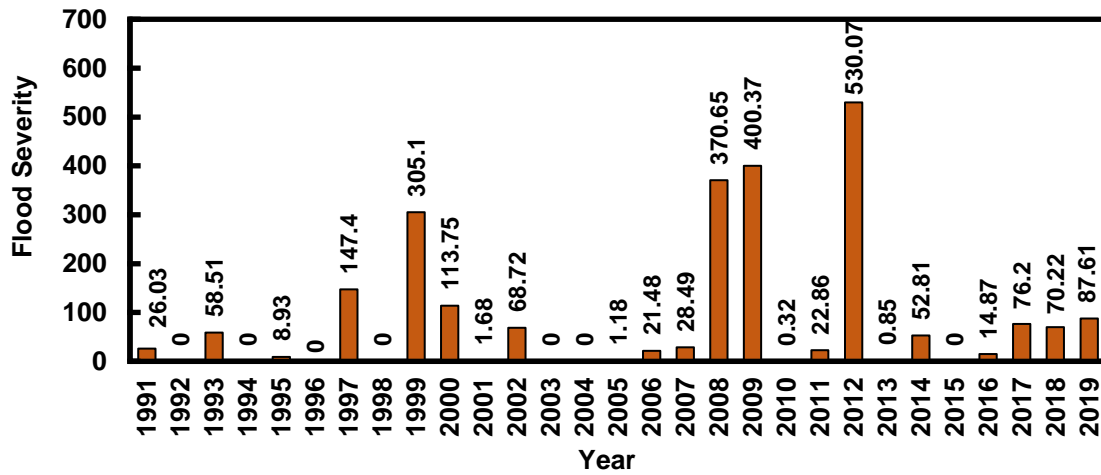
**Figure 5** - Frequency of flood occurrences based on severity levels at the 9 sites between 1991 and 2019.



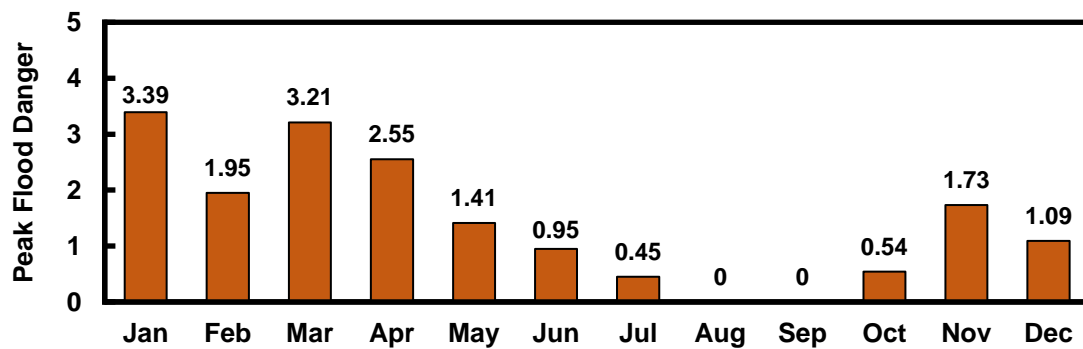
**Figure 6** - Frequency of Flood Situations per month based on severity for the 9 sites combined between 1991 and 2019



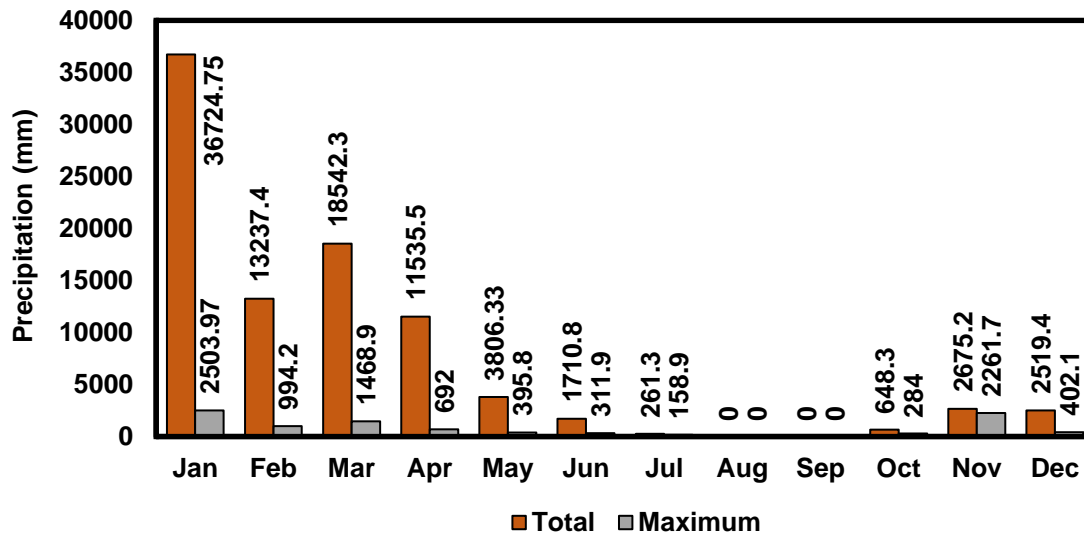
**Figure 7** – Monthly Combined Severity of Flood Situations for the 9 sites between 1991 and 2019



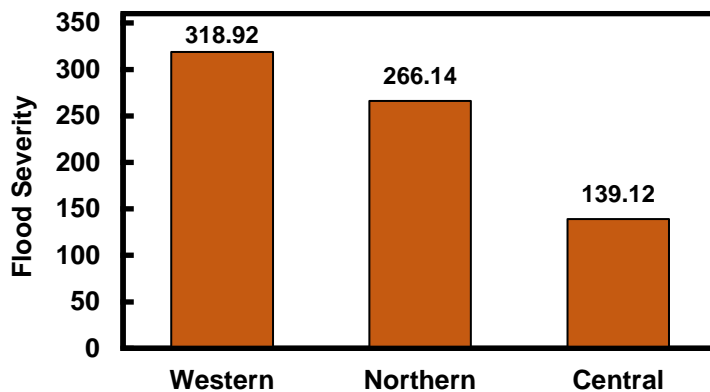
**Figure 8** - Yearly Combined Severity of Flood Situations for the 9 sites between 1991 and 2019



**Figure 9** – Monthly Peak Flood Severity of Floods between 1991 and 2019



**Figure 10** – Monthly Total and Maximum Precipitation during Flood Situations



**Figure 11** - Average Flood Severity for the Different Geographical Divisions in Fiji

Figure 11 compares the severity of floods based on the geographical divisions in Fiji. This has been done by getting the sum of severity for all flood events at each division and then evaluating the mean of the combined severity based on the number of sites at each division. Ba, Lautoka, Nadi, Sigatoka and Rakiraki which lie in the western division had the highest average combined severity. This was followed by the northern division which consist of Labasa and Savusavu. Average severity of floods was the lowest in the central division. Suva and Nausori are part of the central division. It is interesting to note that the central division generally experiences more rainfall when compared to the western and northern division, but the severity of flood is the lowest in this area. Furthermore, the average maximum peak severity during a flood situation in the western division was 2.89. This measure was 2.12 in the northern division

and 2.25 in the central division. This illustrates that when compared with flood events in the northern and central division, the floods of the western division reach higher peak danger.

The statistics of the severest floods that occurred at each of the 9 study sites during the study period has been presented in Table 3. It presents the five-number summary for the  $P$ ,  $AWRI$  and  $I_F$  for the severest flood at each site. The flood with the highest  $I_F^{acc}$  has been classified as the most severe. It can be evaluated from these results that in all areas, the severest flood started between November and April. The severest flood at five out of the nine sites started in January. The highest amount of rainfall during a flood situation was recorded for Ba followed by Rakiraki and Lautoka. Apart from Savusavu, the severest flood for each site occurred after the year 2008. Lautoka recorded the maximum peak danger among these events with a value of 3.39 for the January 2012 flood. Nadi's severest flood also started in January 2012 and reached a peak danger of 2.53. The highest mean  $I_F$  was during the Ba flood ( $Mean I_F \approx 1.16$ ) and the lowest average was during the Suva flood ( $Mean I_F \approx 0.69$ ). The flood events prior to 2010 mostly coincide with the list of flood situations in Fiji between 1840 and 2009 presented by McGree et al. (2010).

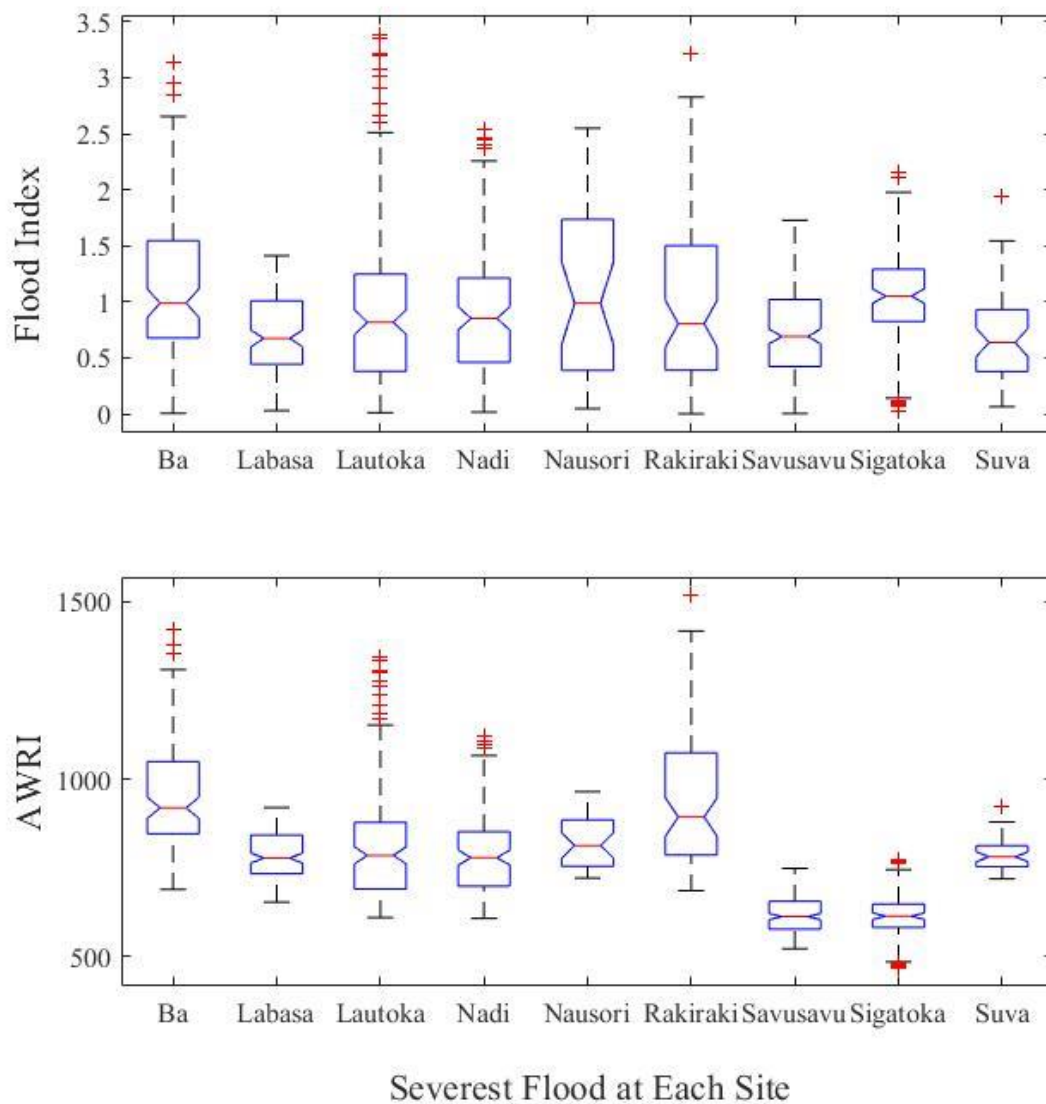
**Table 3** - Statistics of the Severest Flood Event for Each of the 9 Study Sites

Statistic		Minimum	Lower Quartile, Q1	Median, Q2	Upper Quartile, Q3	Maximum	Mean, $\mu$	Standard Deviation, $\sigma$
Ba (January 2009)	$P$	0.00	0.00	3.20	16.40	500.00	20.28	56.07
	$AWRI$	689.44	848.76	919.27	1046.13	1419.60	960.16	163.68
	$I_F$	0.00	0.69	0.99	1.53	3.13	1.16	0.70
Labasa (January 2008)	$P$	0.00	0.00	2.25	15.90	225.80	15.19	30.43
	$AWRI$	654.26	733.97	777.95	842.47	920.00	787.38	67.91
	$I_F$	0.03	0.45	0.67	1.01	1.41	0.72	0.35
Lautoka (January 2012)	$P$	0.00	0.00	0.61	8.50	362.60	16.58	48.13
	$AWRI$	610.39	690.84	785.50	878.15	1343.04	822.12	173.43
	$I_F$	0.01	0.38	0.82	1.25	3.39	0.99	0.80
Nadi (January 2012)	$P$	0.00	0.00	0.20	9.38	291.90	16.00	42.25
	$AWRI$	607.99	699.08	779.10	852.60	1122.86	790.92	120.59
	$I_F$	0.02	0.46	0.85	1.21	2.53	0.91	0.59
Nausori (April 2019)	$P$	0.00	0.40	1.10	11.00	132.40	17.50	34.05
	$AWRI$	721.89	755.10	813.28	885.76	964.83	824.28	75.02
	$I_F$	0.05	0.39	0.99	1.74	2.55	1.10	0.77
Rakiraki (March 2012)	$P$	0.00	0.00	0.00	3.50	450.40	17.34	64.32
	$AWRI$	685.83	788.55	893.57	1070.38	1516.77	947.32	203.02
	$I_F$	0.00	0.40	0.81	1.49	3.21	1.01	0.78



Savusavu (November 1999)	<i>P</i>	0.00	0.00	1.00	12.75	170.30	11.60	24.00
	<i>AWRI</i>	522.97	577.97	613.20	656.35	749.08	617.75	53.40
	<i>I<sub>F</sub></i>	0.00	0.42	0.69	1.02	1.73	0.73	0.41
Sigatoka (January 2009)	<i>P</i>	0.00	0.00	0.80	11.00	183.00	11.98	26.55
	<i>AWRI</i>	469.86	582.69	614.40	648.03	771.33	611.17	69.48
	<i>I<sub>F</sub></i>	0.03	0.83	1.05	1.29	2.16	1.03	0.49
Suva (February 2014)	<i>P</i>	0.00	0.20	6.00	11.45	206.60	19.22	39.17
	<i>AWRI</i>	719.48	753.55	781.52	812.42	923.31	787.68	42.48
	<i>I<sub>F</sub></i>	0.06	0.38	0.64	0.92	1.95	0.69	0.39

Figure 12 shows the distribution of the  $I_F$  and *AWRI* for the major floods in each area in the form of box plots. It shows that only the severest floods in Ba, Lautoka and Rakiraki reached extreme severity ( $I_F \geq 2$ ). The distribution shows that the median  $I_F$  was around 1 (Low – Moderate) for most of the flood situations. The peak danger values from Table 2 are mostly identified as outliers in the box plot, with the exclusion of flood events in Labasa, Nausori and Savusavu, which have no outliers. The *AWRI* for all the flood situations approximately ranged between 500 mm and 1500 mm. The maximum *AWRI* was recorded at Rakiraki and the minimum at Sigatoka. However, these have been classified as outliers in the box plot. Savusavu, Suva and Sigatoka generally have a smaller *AWRI* range when compared to the other sites. Rakiraki has the biggest range, followed by Ba and Lautoka.



**Figure 12** - Box Plot of the Flood Index and AWRI for the severest flood event recorded at each site based on Table 2

Table 4 consists of a set of sub tables that lists the 10 severest flood events for each of the nine sites that occurred during the study period. The classification of floods in this table has been done with the criteria  $I_F > 0$ . It clearly shows the onset date, severity, peak danger, duration, total AWRI, total precipitation and maximum AWRI for the nine sites. The flood situations for each site are ranked according to their severity with 1 being the most severe and 10 being the least severe. The flood and water intensive properties can be extracted from these tables for

further analysis. A brief analysis of the three most severe flood events at each study site has been discussed as well.

**Table 4** - Analysis of 10 severest Flood Situations for (a) Ba (b) Labasa (c) Lautoka (d) Nadi (e) Nausori (f) Rakiraki (g) Savusavu (h) Sigatoka (i) Suva from 1991 to 2019

Site	Onset Date $t_{onset}$	Severity $I_F^{acc}$	Peak Danger $I_F^{max}$	Duration (Days)	Total AWRI (mm)	Total Precipitation (mm)	Maximum AWRI
<b>(a) Ba</b>							
1	9-1-2009	131.57	3.13	113	108498.30	2292.00	1419.60
2	25-1-2012	74.03	1.95	118	98504.41	2259.93	1143.55
3	18-1-1999	51.09	1.19	112	89016.81	2104.40	967.28
4	22-2-2008	21.58	0.82	66	50464.86	980.20	878.65
5	24-3-2007	7.19	0.89	18	14068.33	359.50	895.58
6	8-3-1997	5.70	0.95	17	13030.82	399.90	909.57
7	29-1-2008	4.94	0.49	19	14230.87	502.10	803.51
8	28-1-1997	3.68	0.71	13	9805.91	347.90	854.61
9	5-3-2011	3.30	0.40	17	12470.94	260.00	781.24
10	18-2-2011	1.76	0.42	8	5916.71	234.30	786.18
<b>(b) Labasa</b>							
1	14-1-2008	101.19	1.41	140	110233.00	2127.2	920.00
2	20-2-2002	34.10	1.80	52	40273.33	877.40	994.02
3	15-2-2017	27.98	1.04	54	40395.16	994.20	848.96
4	6-4-2000	23.24	1.29	46	34296.49	682.70	896.02
5	4-2-2006	20.21	1.06	39	29175.15	728.40	852.53
6	17-4-1997	15.54	1.14	37	26980.84	547.30	866.71
7	4-4-2018	13.21	1.17	24	18102.58	498.30	872.86
8	5-3-1997	7.16	0.82	20	14344.65	413.30	806.31
9	13-1-2009	6.91	0.94	14	10407.04	388.10	828.90
10	31-3-1995	4.54	0.51	15	10600.17	252.60	747.25
<b>(c) Lautoka</b>							
1	23-1-2012	149.14	3.39	151	124140.4	2504.00	1343.04
2	18-1-1999	41.95	1.34	72	52868.45	1449.90	898.66
3	10-1-2009	35.87	1.79	60	44255.15	1197.10	997.00
4	25-1-1997	9.88	0.93	23	16125.25	491.20	809.24
5	12-3-2009	7.92	0.52	40	26034.53	441.10	720.70
6	7-3-1997	6.94	0.86	18	12448.88	298.00	793.48
7	22-2-2008	6.05	0.59	21	14078.19	319.40	735.71
8	16-4-1999	5.84	0.59	24	15857.69	273.70	735.01
9	31-1-2008	3.52	0.41	16	10491.25	314.00	696.77
10	6-3-2011	3.09	0.34	19	12221.40	315.30	681.09
<b>(d) Nadi</b>							
1	23-1-2012	116.60	2.53	128	101237.80	2048.30	1122.86
2	27-1-1999	40.45	1.18	103	70536.55	1399.80	845.92

3	8-1-2009	35.85	1.76	63	45417.79	1318.30	964.49
4	3-3-2017	16.77	1.04	38	26400.97	534.70	818.15
5	11-3-2000	11.09	0.86	34	22820.32	481.70	779.66
6	7-2-2017	7.97	0.65	22	14928.24	626.80	738.18
7	7-6-2012	7.61	0.86	25	16667.72	311.90	781.26
8	26-2-1993	7.00	0.85	22	14730.79	731.30	778.09
9	7-3-1997	5.79	0.89	15	10251.57	377.80	787.18
10	4-4-2016	5.33	0.89	14	9552.28	362.20	786.65

(e) Nausori

1	16-4-2019	36.35	2.55	33	27201.38	577.60	964.83
2	19-1-2019	20.52	1.35	32	24946.59	656.50	848.60
3	21-4-2002	16.28	1.25	26	20231.53	391.50	838.77
4	17-12-2016	7.48	1.09	11	8616.91	372.80	823.48
5	9-12-1999	6.90	0.93	11	8560.06	257.40	807.26
6	5-4-1993	6.86	0.91	14	10708.43	216.70	805.39
7	2-1-1993	5.49	1.67	10	7706.65	325.20	879.94
8	12-3-1993	3.68	0.88	8	6096.06	273.90	802.45
9	3-4-2002	3.54	0.43	16	11820.88	237.80	758.87
10	26-3-2019	3.13	1.03	7	5325.35	136.70	817.24

(f) Rakiraki

1	28-3-2012	69.85	3.21	69	65364.81	1196.40	1516.77
2	16-1-2008	66.82	1.48	109	91992.43	1762.10	1068.36
3	4-3-1997	45.33	1.54	95	76834.75	1468.90	1083.74
4	9-1-2009	33.22	1.76	57	47661.10	1277.50	1141.15
5	24-1-2012	25.43	1.01	57	45644.09	1102.40	947.62
6	28-4-2000	15.41	0.72	44	34140.72	692.00	872.53
7	30-1-1997	4.02	0.76	13	9948.46	337.00	882.66
8	9-3-2000	3.43	0.48	17	12537.72	333.80	810.74
9	16-2-2011	3.22	0.50	14	10427.80	338.70	815.59
10	17-6-2000	2.92	0.40	16	11719.36	233.80	789.89

(g) Savusavu

1	27-11-1999	141.65	1.73	195	120460.60	2261.70	749.08
2	14-4-1997	35.89	2.44	52	31876.56	691.00	842.04
3	15-1-2008	28.78	1.75	47	28331.59	729.30	751.33
4	23-6-2008	10.40	0.95	27	15472.41	294.80	646.92
5	10-1-2009	6.76	0.88	17	9770.38	437.30	638.39
6	9-4-2008	4.98	0.77	18	10060.12	217.00	623.49
7	13-5-2008	4.68	0.59	17	9497.20	221.70	599.88
8	21-2-2002	4.15	0.54	21	11518.62	354.40	593.70
9	7-3-1991	3.98	0.50	15	8361.13	247.70	588.50
10	29-1-2009	3.05	0.41	16	8761.42	202.00	576.56

(h) Sigatoka

1	8-1-2009	128.59	2.16	125	76395.63	1497.39	771.33
2	14-1-2008	102.54	1.43	138	78766.74	1418.20	667.53
3	29-3-2012	43.69	1.61	57	32723.18	615.40	693.16
4	18-3-2000	35.32	1.46	65	35264.69	634.20	671.84

5	26-3-2018	34.55	1.55	56	30965.17	588.10	684.26
6	30-1-2012	18.96	0.81	49	25501.07	496.50	580.92
7	10-2-2017	17.23	0.95	45	23393.47	549.53	600.34
8	26-2-2014	9.19	0.49	37	18530.93	401.17	535.05
9	13-2-2018	9.07	0.47	34	17115.92	429.00	531.96
10	9-2-2000	8.11	0.66	26	13255.84	275.20	559.54
(i) Suva							
1	26-2-2014	32.62	1.95	47	37021.16	903.30	923.31
2	24-3-1993	22.72	1.44	36	28111.03	565.90	868.86
3	18-4-2019	21.49	1.76	29	22990.68	511.40	902.80
4	2-2-1991	12.52	1.09	28	21305.83	454.40	831.07
5	31-3-2012	11.40	0.82	28	21185.44	456.80	800.92
6	16-5-2014	9.83	1.40	17	13177.47	372.00	864.67
7	2-12-1999	6.29	0.70	16	12081.88	402.10	788.44
8	21-4-2002	5.82	0.78	20	14880.44	335.40	797.02
9	19-4-2007	4.69	0.84	14	10483.14	288.40	804.03
10	4-5-2007	3.54	0.91	8	6083.63	141.60	811.52

The analysis of floods in Ba (Table 4(a)) indicate that the town faced its severest floods in 1999, 2009 and 2012. All these floods started in January and the one in 2009 was the severest and the one which started in 1999 was the least severe. The 2009 flood has been described previously in Figure 3. The 2012 flood lasted for 118 days. Interestingly, this duration was longer than that of the severest flood whereby the flood lasted for 113 days. The severity of the 2012 flood was 74.03 and it reached a peak danger of 1.95. Approximately, 2259.93 mm of rainfall was recorded during this flood period. The duration of the 1999 event was 112 days with severity 51.09 and it reached peak danger of 1.19. Approximately, 2104.4 mm of precipitation was recorded during this flood. All the 10 severest floods in Ba started between January and May and on average, the ones which started in January were the most severe.

As seen in Table 4(b), the most significant flood event recorded in the town of Labasa reached total severity of 101.19 and lasted for 140 days. This flood started in January 2008 and reached a peak danger of 1.41. Approximately, 2127.2 mm of rainfall was recorded during this event. The second severest flood at this site occurred in February 2002 and reached a peak severity of 1.8. The total severity of this event was 34.1 and this event lasted for 52 days. Other notable floods occurred at this site in 2000, 2006 and 2017 and reached peak dangers of 1.29, 1.06 and 1.04, respectively. Apart from the severest flood, all other flood situations recorded

accumulated rainfall of less than 1000 mm. The 10 severest flood events at this site started during the first five months of the year.

As per Table 4(c), the severest flood in the city of Lautoka started in January 2012 and amounted to a total severity of 149.14 and reached extreme peak severity of 3.39 during the 151 days of flood situation. This was also the severest flood event for the 29-year period among all the study sites. During this event, approximately, 2504 mm of rainfall was recorded. The next severest flood at this site occurred in January 1999 and reached peak danger of 1.34 while experiencing total rainfall of about 1449.9 mm. This event lasted for 72 days and had a combined severity of 41.95. The January 2009 floods at this site had a duration of 60 days and reached peak danger of 1.79. This event had a total severity of 35.87 and recorded approximately 1197.1 mm of rainfall. All the 10 severest floods at this site started between December and April.

The most severe floods in Nadi are listed in Table 4(d). The site's severest flood occurred in January 2012 and lasted for 128 days. The accumulated severity during this period was 116.6 and an extreme peak danger of 2.53 was reached. Approximately, 2048.3 mm of precipitation was recorded during this event. The second most severe flood for Nadi started in January 1999 and had a duration of 103 days during which it reached a peak severity of 1.34 and combined severity of 41.95. In January 2009, the site recorded a flood situation that lasted for 63 days and reached peak danger of 1.76. It had a severity of 35.85.

Based on Table 4(e), the severest flood in Nausori lasted for only 33 days but reached extreme peak danger of 2.55 and had a total severity of 36.35. This event started in April 2019. The second most severe flood in the area had a duration of 32 days. This flood reached peak severity of 1.35 and had a combined severity of 20.52. This flood occurred in January 2019. Another notable flood in Nausori occurred in April 2002 which had a duration of 26 days and reached peak danger of 1.25. The total severity of this flood event was 16.28. Approximately, 577.6 mm, 656.5 mm and 391.5 mm of rainfall was recorded for these three flood situations, respectively.

Table 4(f) lists the severest floods in Rakiraki. The March 2012 flood was the severest for the area. The flood lasted for 69 days and reached peak danger of 3.21. It had a combined severity of 69.85 and recorded approximately 1196.4 mm of precipitation during the flood situation. The second and third severest floods in the area had a duration of 109 days and 95 days, respectively. The former had a combined severity of 66.82 and reached peak danger of 1.48

while the latter had a total severity of 45.33 and reached peak severity of 1.54. These two flood events started in January 2008 and March 1997 and recorded rainfall amounts of about 1762.1 mm and 1468.9 mm, respectively.

The severest flood event in Savusavu had the longest duration amongst all sites during the 29-year period. As shown in Table 4(g), the flood started in November 1999 and lasted for 195 days, during which it had reached a peak danger of 1.73 and recorded total severity of 141.95. Approximately, 2261.7 mm of rainfall was recorded during this flood situation. The second most severe flood in the area reached extreme peak danger of 2.44 during the 52 days period. This event, which started on April 1997, recorded approximately 691 mm of rainfall, and had a severity of 35.89. The January 2008 flood event lasted for 47 days and reached peak danger of 1.75. This event had a severity of 28.78 and total rainfall of about 729.3 mm.

The most severe flood events in Sigatoka started in January 2009, January 2008, and March 2012. The January 2009 flood lasted for 125 days, reached peak danger of 2.16 and had a combined severity of 128.59. Approximately, 1497.39 mm of rainfall was recorded during this period. The 2012 flood event had a duration of 138 days and reached a peak severity of 1.43 while amounting to a total severity of 102.54. This event recorded about 1418.2 mm of rainfall. The flood which started in March 2012 experienced approximately 615.4 mm of precipitation during the 57 days and reached peak danger of 1.61. This flood situation had a severity of 43.69. The list of the 20 severest flood events in Sigatoka is presented in Table 4(h).

Based on Table 4(i), the severest flood in Suva started in February 2014 and lasted for 47 days. This flood had a total severity of 32.62 and reached peak severity of 1.95. Approximately, 903.3mm of rainfall was recorded during this event. The second most severe flood started in March 1993 and had a severity of 22.72 and reached a peak danger of 1.44. This event lasted for 36 days and experienced approximately 565.9 mm of rainfall. The April 2009 flood in Suva had a duration of 29 days during which it recorded about 511.4 mm of rainfall. This event had a severity of 21.49 and peak danger of 1.76.

**Table 5** - Analysis of Flood Situations with Extreme Severity at the 9 Study Sites from 1991 to 2019

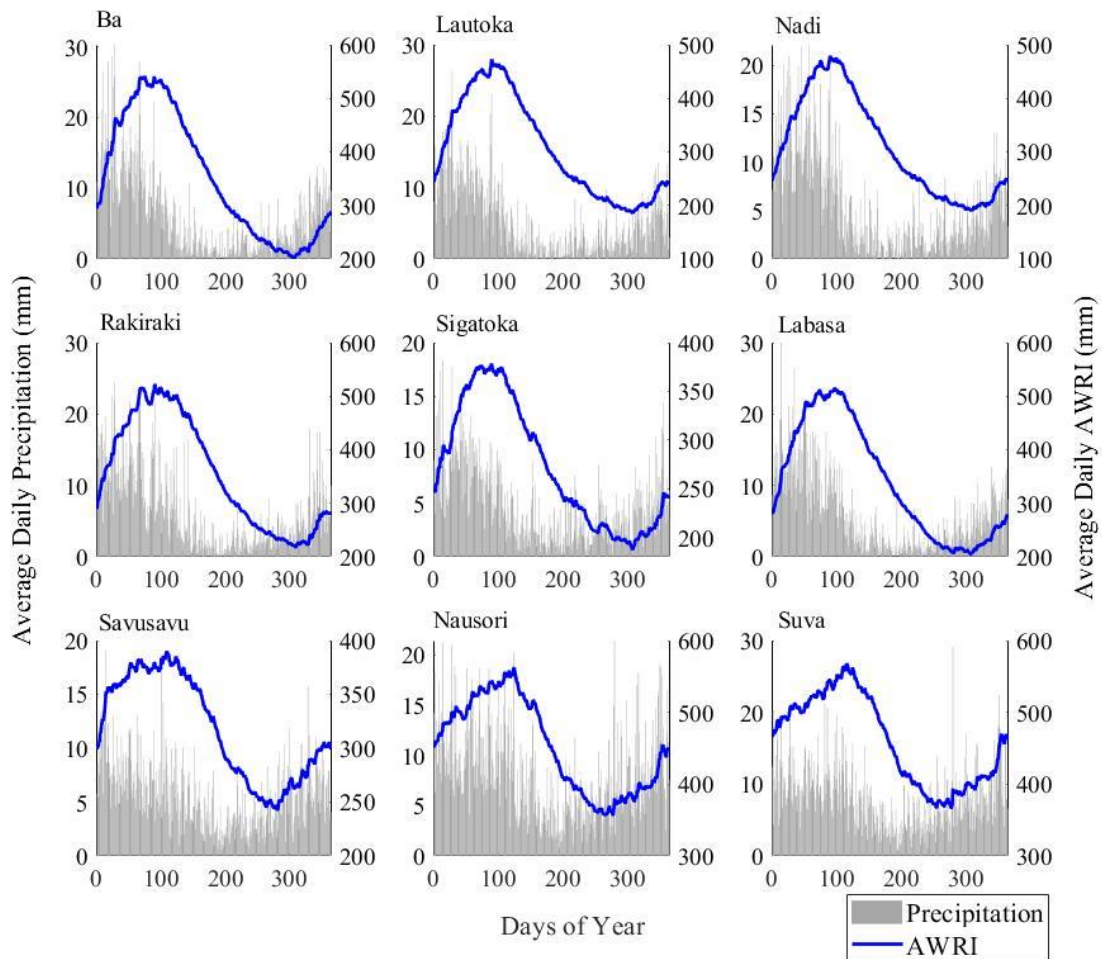
Site	Onset Date $t_{onset}$	Severity $I_F^{acc}$	Peak Danger $I_F^{max}$	Duration (Days)	Total AWRI (mm)	Total Precipitation (mm)	Maximum AWRI
Ba	11-1-2009	38.86	3.13	16	20086.07	1236.30	1419.60
Labasa	No Extreme Floods						
Lautoka	30-3-2012	49.27	3.39	18	21626.62	692.70	1343.04
Nadi	31-3-2012	18.63	2.53	8	8649.45	326.50	1122.86
Nausori	23-4-2019	13.71	2.55	6	5635.16	213.60	964.83
Rakiraki	1-4-2012	22.52	3.21	9	11997.25	564.10	1516.77
Savusavu	4-5-1997	4.60	2.44	2	1647.83	148.00	842.04
Sigatoka	11-1-2009	2.11	2.11	1	763.85	183.00	763.85
	15-1-2009	4.32	2.16	2	1541.56	84.30	771.33
Suva	No Extreme Floods						

Table 5 lists the flood situations with extreme severity during the 29-year period. These are flood situations which have  $I_F > 2$ . Flooding's of 2009 and 2012 were the most extreme. Significant damages were caused by floods during these years (Lal 2009; Yeo 2013). Labasa and Suva did not record any extreme flood events. The duration of extreme floods in Savusavu, and Sigatoka was low as well. The most extreme flood events occurred in Ba, Lautoka, Nadi and Rakiraki and all these sites are in the western side of Fiji. The Ba and Lautoka floods were extreme for 16 and 18 days singly while the Nadi and Rakiraki floods were extreme for 8 and 9 days, respectively.

As shown in Figure 13, the seasonality of rainfall and AWRI was investigated for each of the nine study sites. This was done by obtaining the daily average precipitation and daily average AWRI for the 29 years for each study site. All sites exhibited a generally similar pattern whereby there is a higher occurrence of rainfall and greater AWRI values in the first few months and the last two months of the year. The sites in the western side of Fiji generally experience less rain the middle of the year when compared to the other sites. It can also be seen



that Suva and Nausori experiences consistent rain almost throughout the entire year and generally have higher AWRI. It is interesting to note that the rainfall pattern in Savusavu is quite similar to the central division and the rainfall pattern in Labasa resembles more closely to the western division even though both Labasa and Savusavu are on the same island in the northern division.



**Figure 12** – Daily Average Rainfall (Precipitation) and Daily Average AWRI for the nine study sites from 1991 till 2019.

The results obtained in this study for the nine study sites used  $I_F$ , which is the normalized form of  $AWRI$ . As presented in these results,  $I_F$  made it easier to determine a flood situation when compared to  $AWRI$  or raw precipitation data. This is because a simple condition  $I_F > 0$ , can be used to classify a flood situation. Such a condition cannot be used with  $AWRI$  and raw precipitation values. The comparison of determining flood based on the two can be done using

Figure 4 and Figure 13. In Figure 4,  $I_F$  and  $P$  for the first 180 days of 2009 are plotted for each site and in Figure 13, average  $AWRI$  and average  $P$  for the 29-year period for each site are plotted.

#### 4 Conclusion

The Flood Index ( $I_F$ ) was successfully computed and the duration, severity and intensity of flood events that occurred between 1991 and 2019 for the nine sites in Fiji was determined and analysed.  $I_F$  was determined to be a good measure to monitor flood events based on its ability to accurately determine flood situations in different parts of Fiji. The capability to categorize a flood event based on the value of  $I_F$  allowed the classification of flood severity as either low, moderate, severe, or extreme.

Results showed that severe floods in the country were more likely to occur between November and April, which is also the wet/cyclone season in Fiji. Most of the severe floods in the western side of Fiji occurred in the month of January. Overall, the severity of floods in January were high as well. This shows that effective flood preparation and risk mitigation strategies need to be implemented for these months. Likewise, almost all the study sites experienced high rainfall during these months. To add on, on average, floods in the western side of Fiji were more severe and reached greater peak dangers showing the vulnerability of the sites in this region to floods.

A major outcome of this paper was presenting the water and flood intensive properties of the 10 severest flood events for each site. Statistics such as these and the evaluation of the severest flood at each site during the study period can be further explored by relevant organizations to get more insights on previous flood situations. These insights on past events can be explored to make informed decisions regarding future flood threats. Furthermore, as mentioned previously, the method presented in this study uses a time-dependent reduction function to account for physical and geographical factors that contribute to a flood situation, and even though this method has been accepted to be fairly accurate, further studies are required to test the various time reduction functions against how they reduce  $P_E$  by experimental methods. In addition, studies on how a physical rainfall-run off model can be connected to further improve the time factor could assist in enhancing the presented method further.

Moving on, the methods applied in this study can be replicated to study flood events in other small Pacific Island countries which face the risk of floods. Furthermore, it will also be interesting to monitor flood events in these countries on hourly timescales. However, this will be subjected to the availability of hourly rainfall data for different sites in the country. Overall,

the results presented in this paper can be used by the government, organizations, and individuals to better prepare for floods and to develop efficient flood mitigation strategies that will help to save lives, money, and other resources. To conclude, based on the performance of  $I_F$  in determining the duration, severity and intensity of flood situations, the index can be accepted as a viable and cost-effective tool for monitoring floods.

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