

EXTREME RIVER BEHAVIOUR IN THE PACIFIC ISLANDS - CASE STUDIES FROM SAMOA AND FIJI

JAMES P. TERRY

*Head of Geography Department, The University of the South Pacific,
PO Box 1168 Suva, Fiji Islands*

RAY A. KOSTASCHUK

*Department of Geography, University of Guelph
Guelph, Ontario, N1G 2W1, Canada*

High-magnitude river floods on steep terrain volcanic islands in the South Pacific are a recurrent problem, especially during tropical cyclones (hurricanes), but our knowledge of Pacific island fluvial behaviour continues to remain poor. In response, this paper examines flood hazards in the Vaisigano River in Samoa and the Rewa River in Fiji. Tropical cyclone (TC) hydrographs show very large, concentrated peak discharges, influenced by the intensity and duration of the storms and their track direction in relation to river basin orientation. Flow data for the Vaisigano River give a 'near-catastrophic' flood variability index value of 0.6, compared to a world mean of 0.28. Peak TC-generated discharges for the Rewa River are related to the strength of the Southern Oscillation, and storms during El Niño events produce the largest floods. The log Pearson Type III distribution provides a good fit to the measured data of flood discharges, but the widely accepted generalized Pareto distribution performed poorly. Changing Pacific climate and associated ocean warming may increase tropical cyclone intensity. If so, then future river floods in Samoa and Fiji may be more severe, and associated socio-economic vulnerability of developing island nations will become worse.

INTRODUCTION

Large river flood events have major impacts on environmental and socioeconomic conditions on floodplains [1,2]. Most studies of river floods have focused on humid temperate climates [3], even though large floods are probably more frequent and significant in humid tropical regions [4]. In the developing island nations of the South Pacific, tropical cyclones (TCs), known elsewhere as 'hurricanes' and 'typhoons', are a recurrent problem. Hydrological short-circuiting on mountainous volcanic islands tends to be rapid, owing to 1. orographic effects of the rugged terrain; 2. natural rainforest clearance; and 3. steep slopes and permeable volcanic soils which promote rapid transfer of rain water to stream channels. Intense TC precipitation therefore generates enormous river floods that cause widespread damage to agriculture, homes and commercial property.

In Fiji for example, destructive floods during TC Kina in 1993 caused damage

exceeding F\$88 million [5], and in 2003 during TC Ami (Figure 1), terrible flooding tragically lost 17 lives. Despite their hazard on South Pacific islands, TC-induced floods are poorly understood. This paper examines the impact of tropical cyclones on the flood hydrology in the Vaisigano River on Upolu Island in Samoa and the Rewa River on Viti Levu island in Fiji (Figure 2). We focus on 1. the role of TCs in flood generation, 2. links between TC floods and the Southern Oscillation Index, 3. the flood variability index, and 4. the frequency series (partial duration and annual maximum) of flood flows. For the purposes of this paper, a flood is a flow that exceeds the channel banks.



Figure 1. Flooding of the northern town of Labasa on Vanua Levu island, Fiji, during Tropical Cyclone Ami in January 2003. Source: Fiji Meteorological Services

CLIMATE AND TROPICAL CYCLONES IN THE SOUTH WEST PACIFIC

Samoa and Fiji have very wet tropical climates. There is distinct seasonality in precipitation; a hot and wet summer season lasts from December to May and a cooler and drier winter season lasts from June to November. Moisture is normally delivered by the dominant South East Trade Winds. On both Upolu and Viti Levu islands, orographic lifting gives annual rainfalls in excess of 5000 mm in the interior volcanic highlands compared to approximately 2500 mm on the windward coasts.

The most extreme meteorological conditions occur during tropical cyclones in the wet season. Often these storms form embedded in the South Pacific Convergence Zone (SPCZ) during its summer proximity to Samoa and Fiji, in optimal conditions bringing torrential precipitation and causing extreme floods. A TC is an intense low pressure system that develops over a large mass of warm ocean water ($>26.5^{\circ}\text{C}$), organised in bands of cloud rotating clockwise in the southern hemisphere. Violent winds circulate around a central calm eye, where atmospheric pressure at sea-level may drop below 930 millibars. In the entire SW Pacific, approximately ten TC events occur per season (Table 1). From 1970 to 2004, 18 TCs tracked close to Samoa, and 37 TCs entered Fiji waters

from 1970 to 1998. The formation of TCs, and their frequency, depends on several factors including sea surface temperature (SST), the vertical lapse rate of the atmosphere, vertical wind shear, mid-tropospheric relative humidity, and the existence of a centre of low-level cyclonic vorticity [6]. Standing oscillations in atmospheric surface pressure in the South Pacific, termed the Southern Oscillation (SO), have been shown to affect TC frequency [7,8]. The Southern Oscillation Index (SOI) is generally anticorrelated with SST [9]. Thus, TCs in the South Pacific are often experienced in the developing phase of El Niño events, because convective storms are generated as the eastward-migrating pool of warm ocean water traverses north of the island groups. Twenty six of the 37 TCs in Fiji waters during 1970-98 occurred in months with negative SOI.

Table 1. Basic data on tropical cyclones in the South Pacific

TC season	December – May
Months with highest frequency	January and February
Average seasonal frequency	9.4 TCs
Maximum annual number	17 TCs in 1997
El Niño effects	Occurrence of TCs out of normal season e.g. TC Keli in June 1997
Most intense TC on record	TC Zoe in December 2002 Minimum pressure – 890 mb 10-minute winds – 287 km/h 3-second gusts – 350 km/h.

STUDY RIVERS

Vaisigano River, Samoa

The Vaisigano River is the largest river on Upolu island, flowing north to the coast through the capital city of Apia (Figure 2). It is also the most extensively studied river in Samoa. The Vaisigano drains an area of approximately 33 km² and its basin is 11 km long and 5 km wide at the widest section. The geology comprises moderately to strongly weathered olivine basalts and basaltic andesite rocks, occurring as dark lava flows, dykes, rubbly scoria and tuffs. Soils developed on the bedrock are clays with volcanic boulders. The river basin is bounded to the south by the central chain of volcanic cones that form the ENE-WNW highland spine of the island. The watershed rises to 1160 m at Mount Fito, the highest point on Upolu. The geomorphology can be broadly divided into four units. Near the coast is an undulating coastal plain and river floodplain of recent alluvium, rising from sea level to about 100 m. This area is urbanized by Apia. From 100 m to 300 m is a region of lowland hills with villages, plantations, scrub and grazing lands. Rising steeply from 300 m to 700 m is a dissected upland region of escarpments and volcanic ridges. Above 700 m in the southern area of the basin are a dissected highland volcanic

plateau and a series of volcanic cones and craters. These areas are vegetated by rainforest.

The Alaoa East streamflow station on the Vaisigano River is the only permanent gauging station in Samoa. It has been in operation since 1973 by the Samoan Meteorological Office (SMO), although there are significant gaps in the data. The record of mean daily discharge is nearly complete from 1973-1987, but a storm surge during TC Ofa in 1990 completely destroyed the gauging station as well as the buildings of the SMO in Apia. There are fragmented records from 1988-1998 and complete records from 1999-2001.

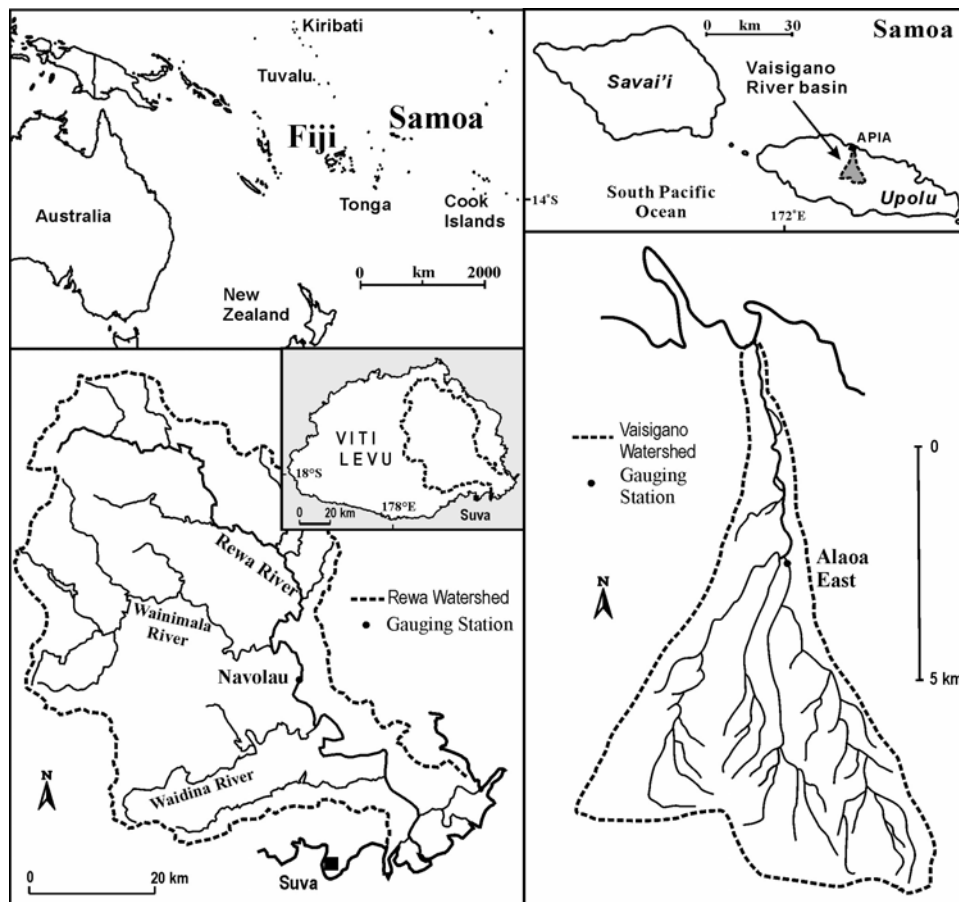


Figure 2. Location of Vaisigano and Rewa rivers in Samoa and Fiji in the South Pacific

Rewa River, Fiji

The Rewa River is the largest fluvial system in Fiji. The basin spans 2900 km², or approximately one third of Viti Levu island. The western portion of the Rewa watershed is located on the Nadrau Plateau where maximum elevation is 1360 m at Mount Victoria. Most of the north and east of the Rewa basin falls within the East Highland, characterized

by hills 300-600 m in elevation. River channels are steep in their upper reaches (mean slope = 0.033) but decrease abruptly downstream (mean slope = 0.002) in the alluvial channels where gauging stations are located. The northern part of the basin is composed mainly of relatively young basaltic rocks and the southern part of older plutonic rocks. Dense tropical rainforest is the natural vegetation, but on the floodplains this is replaced by grazing pasture and subsistence farming. For the Rewa River, we focus on mean daily discharge from Fiji Public Works Department gauging station at Navolau. This gauging station drains 1960 km² and has a 25 year continuous record from 1971. Bankfull discharge is estimated at 2000 m³/s.

LARGE RIVER FLOODS

Figure 3 shows mean annual and maximum daily discharges for years with nearly complete (>300 days) flow records for the Vaisigano River in Samoa. Mean annual precipitation is recorded only for 1973 (5816 mm), 1976 (4777 mm) and 2001 (2994 mm). River flood variability may be expressed by the standard deviation of the logarithm (base 10) of the annual maximum flood series [10]. The world mean of this index is 0.28 and they propose that values greater than 0.6 are ‘catastrophic’ floods. The flood variability index for the measured data is 0.6, which is at the threshold for catastrophic flooding. The ‘near-catastrophic’ flood index for the Vaisigano indicates frequent, high magnitude overbank floods related to the biennial occurrence of TCs affecting Samoa.

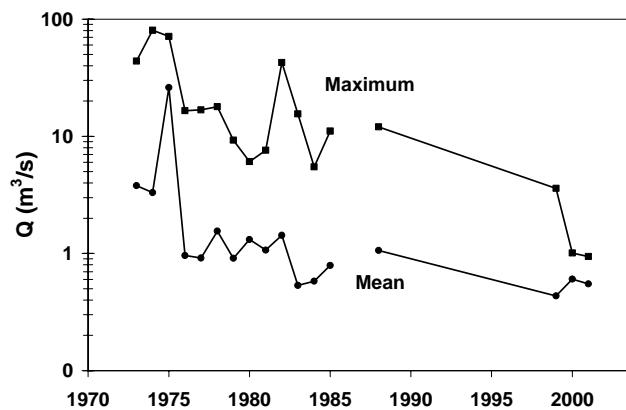


Figure 3. Annual daily mean and maximum discharge (Q) for the Alaoa East station on the Vaisigano River, Upolu Island, Samoa. Source: Samoa Meteorological Office

Table 3 presents the chronology of TCs that have caused overbank floods at Navolau on the Rewa River during 1970-97, showing that this site experiences a high frequency of flooding. Tropical cyclones that have the greatest impact on river flows are those that

pass closest to the watershed. The centres of TCs Wally, Bebe and Kina (Table 3), for example, all tracked within 50 km of the centre of the Rewa basin. Most TCs approach Fiji from the northwest. This path maximizes peak flows in the Rewa by delivering precipitation in the upper portions of the watersheds before the lower reaches, thereby concentrating discharge over a shorter period of time at Navolau. Also, the gauging station is located just downstream of the Wainimala confluence where flood waves from the upper Rewa and Wainimala rivers interact constructively. Long term TC-generated flood statistics are shown in Table 4.

Table 3. Chronology of tropical cyclones that have caused overbank floods in the Rewa River, 1970-1997. Storm Duration is the time that the TC occupied Fijian waters, Q_p is the peak daily discharge, and Flood Duration is the period that the flow exceeded bankfull stage

Tropical Cyclone	Storm Duration (d/m/y)	Q_p (m^3/s)	Flood Duration (days)
Priscilla	14/12/70 - 18/12/70	2003	1
Bebe	19/10/72 - 06/11/72	6711	3
Lottie	05/12/73 - 12/12/73	2304	2
Tina	24/04/74 - 28/04/74	3100	1
Val	29/01/75 - 05/02/75	2806	2
Wally	01/04/80 - 06/04/80	4218	2
Hettie	27/01/82 - 30/01/82	3311	2
Oscar	28/02/83 - 02/03/83	4533	3
Nigel	19/01/85 - 20/01/85	2734	1
Gavin	04/03/85 - 07/03/85	3960	2
Sina	24/11/90 - 30/11/90	2117	1
Joni	06/12/92 - 13/12/92	3581	2
Kina	26/12/92 - 05/01/93	6923	2
Gavin	04/03/97 - 11/03/97	3927	1
June	03/05/97 - 05/05/97	4015	3

Table 4. Descriptive statistics for cyclone-generated floods in the Rewa River at Navolau gauging station, 1970-1997

number	15
mean (m^3/s)	3756
standard deviation (m^3/s)	1470
skewness	0.902
mean annual frequency of floods	0.54

Tropical cyclones associated with El Niño events often produce extreme floods. In 1997 during the onset of El Niño, six TCs (Freda, Gavin, Hina, Ian, June and Keli) traversed Fiji waters within a period of five months. Most TCs brought torrential downpours and some storms delivered exceptional 1-day rainfalls in excess of 600 mm. The ensuing large floods (Figure 4) caused channel instability and migration, transported very high concentrations of suspended sediments to the coast smothering coral reefs, destroyed farms and crops, and placed difficult economic burdens on both rural village communities and the Fiji nation as a whole. Figure 5 illustrates the link between all measured TC-generated floods in the Rewa River and the SOI.

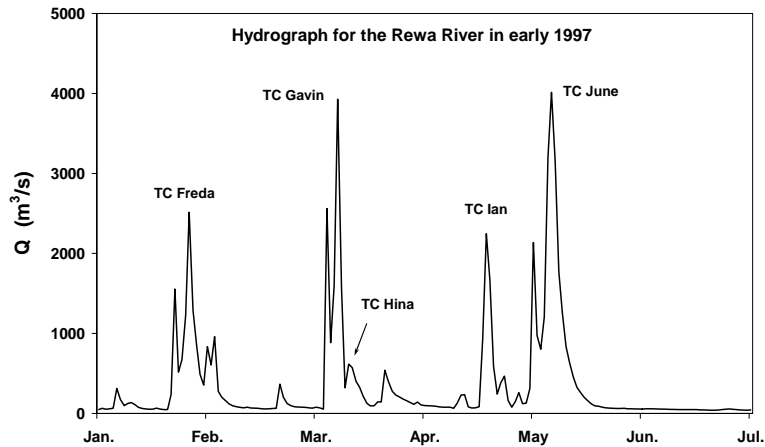


Figure 4. Extreme flood peaks in the Rewa River, Fiji, produced by a succession of tropical cyclones during the onset of the 1997 El Niño event in the South Pacific

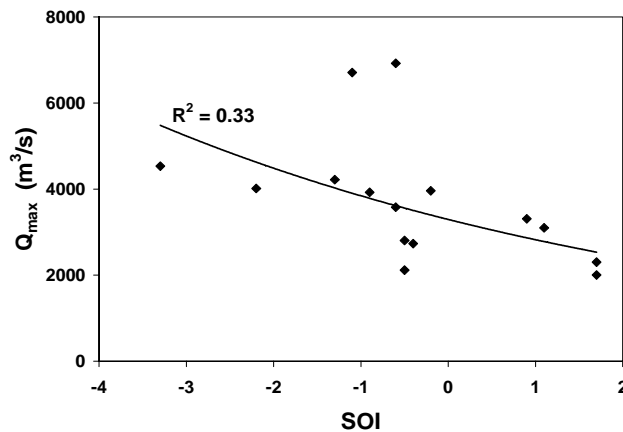


Figure 5. Peak flood discharge (Q_{max}) in the Rewa River at Navolau during tropical cyclones versus SOI for the month that the TC occurred, after Terry *et al.* [11]

For hydrologic frequency modelling, the annual maximum series (AMS) and the partial duration series (PDS) are two approaches commonly used. The AMS approach uses the largest annual value and is widely used, although with some limitations [12]. The PDS considers flows above a certain threshold, e.g. bankfull stage, ensuring that selected peaks are independent of each other [13]. For our analysis of flood flows, the AMS and PDS approach was tested in the Vaisigano and Rewa River respectively (Figures 6 and 7). The log Pearson Type III probability distribution, recommended by the Work Group on Flood Flow Frequency [14], provided the best fit to the measured data in Samoa and Fiji. The generalized Pareto (GP) distribution performed poorly, despite recently gaining broad acceptance [15,16]. This finding underscores the need to test a variety of distributions for flood series from a particular geographic location, rather than assuming a particular distribution for all flood series.

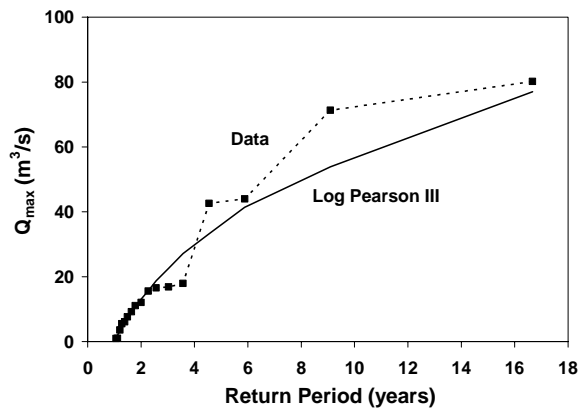


Figure 6. Annual maximum series (AMS) flood frequency curve for the Vaisigano River in Samoa, at Alaoa East gauging station. Q_{max} is annual maximum discharge, Samoa

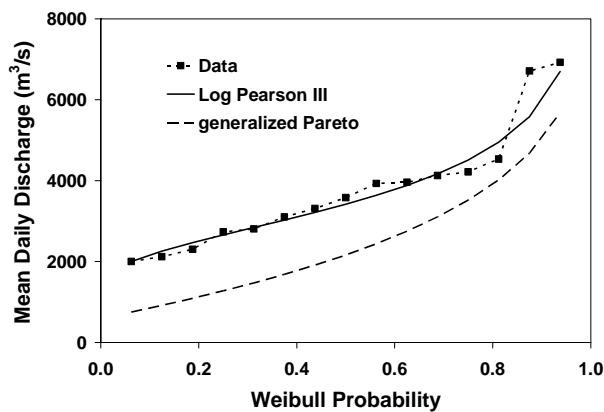


Figure 7. Partial duration series (PDS) flood frequency curve for cyclone-generated floods in the Rewa River, Fiji, at Navolau gauging station

FUTURE CONCERNS

In the future, although many uncertainties remain, scientists now project that Pacific regional climates will experience more sustained El Niño-like conditions owing to global atmospheric and ocean warming [17,18]. Increases in SST above the 26.5°C threshold will not necessarily result in more frequent tropical cyclones and new TC frequencies will likely be related to changes in regional-scale circulation patterns, not simply warmer oceans [19,20]. Some Global Climate Model experiments, however, suggest that TC intensity could increase in the Southern Hemisphere [21,6]. If this prediction is correct, then future river floods in Samoa and Fiji will probably become more severe and associated socio-economic vulnerability of these developing island nations will worsen.

SUMMARY

Tropical cyclones are important for generating extreme river floods in Samoa and Fiji. In the Vaisigano and Rewa rivers, floods are large, brief, isolated events. Large floods are the result of torrential TC precipitation intensities coupled with the environmental characteristics of mountainous volcanic island river basins which promote hydrological short-circuiting and rapid runoff. Flood discharge is augmented when TCs travel along the length of a watershed. Peak flows produced during TCs are inversely correlated with the SOI. The log Pearson Type III distribution provided good fits to measured data of maximum discharges, but the popular generalized Pareto distribution performed poorly. This work continues to increase our knowledge of hydrology in tropical Pacific island environments, where the behaviour of fluvial systems remains poorly understood.

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