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Hazard warning! Hydrological responses in the Fiji Islands to climate variability and severe meteorological events

JAMES TERRY

Geography Department, The University of the South Pacific, PO Box 1168, Suva, Fiji Islands
terry_j@usp.ac.fj

Abstract Extreme meteorological events and their hydrological consequences create hardship for developing nations in the South Pacific. In the Fiji Islands, severe river floods are generated by tropical cyclones during the summer wet season, causing widespread devastation and threatening food security. In January 2003, Hurricane Ami delivered torrential rainfalls and record-breaking floods, owing to the rapid approach of the storm, the steep volcanic topography promoting strong orographic effects and hydrological short-circuiting, and landslides temporarily damming tributary channels then subsequently failing. At the opposite extreme, hydrological droughts are experienced during prolonged El Niño phases. Fiji's population relies on streams for water resources, so episodes of dry season rain failure and low flows over recent decades caused severe water crises. Low discharges in the major Ba River show good correspondence with the SOI, although minimum Q lags behind lowest SOI values by several weeks. Regional ocean warming and more sustained El Niño-like conditions in future may increase the recurrence and intensity of flood-and-drought cycles.

Key words El Niño; Fiji Islands; floods; hydrological droughts; tropical cyclones

INTRODUCTION

For the volcanic Fiji Islands in the tropical southwest Pacific, extreme high and low river flows, i.e. floods and hydrological droughts, are linked to the response of island fluvial systems to tropical cyclones and ENSO-induced periods of prolonged rain failure. These are serious hydrological hazards because of their impacts in the physical and human environment, including channel erosion and siltation, destruction of homes and infrastructure, contamination of water resources, damage to agriculture (threatening food security), and risks to human life and health. Such impacts place a difficult socio-economic burden on small island nations. Improved mitigation of hydrological hazards is therefore a priority in Fiji, but this requires a better understanding of these hazards than currently exists. The aims here are to (a) investigate the severe flood response to Tropical Cyclone Ami in 2003, and (b) describe the relationship between the strength of the ENSO signal measured by the SOI and the magnitude of hydrological drought.

If flood-and-drought cycles become more severe in the future as the Pacific regional climate changes towards more sustained El Niño-like conditions, as many climate scientists now project (see Holland, 1997; Trenberth & Hoar, 1997; Timmermann *et al.*, 1999; Whetton *et al.*, 2000), then such information will improve disaster preparedness and risk management or adaptation.

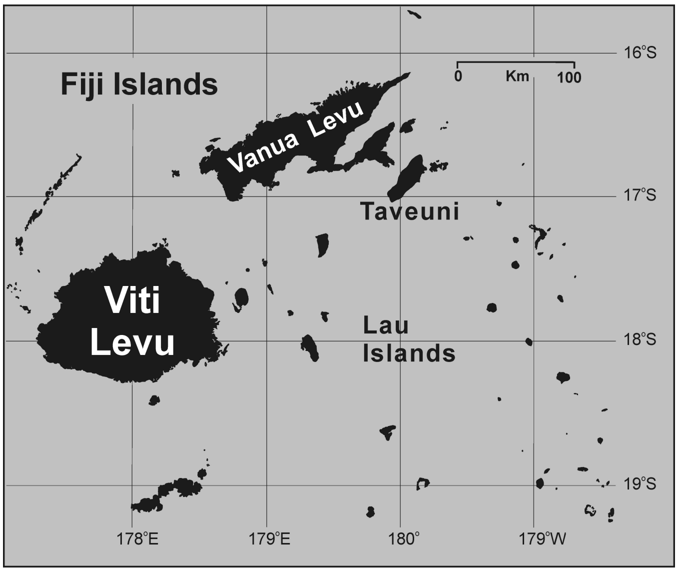

Fig. 1 The Fiji Islands.

FIJI'S CLIMATE

Fiji's tropical latitude (16–19°S) in the southwest Pacific, influenced by the warm southern equatorial ocean current, gives a wet/dry tropical climate. The southeast sides of the main islands face the predominant trade winds and therefore receive more precipitation than the northwest, which is rain-shadowed by interior highlands. The climate is seasonal with a wet season from November to April, when tropical cyclones may occur, and a dry season from May to October. Cyclones are severe storms, often producing extreme rainfalls because Fiji's volcanic mountains force orographic lifting of the spiralling rain bands.

In Fiji's dry season, there is an uneven distribution of rain days; rainfall seasonality is more pronounced for the leeward northwest of the high islands, which receive only 20% of the annual total in the dry months, compared to 33% for the windward side. In years without strong ENSO activity, rainfall benefits from convection along the low pressure South Pacific Convergence Zone (SPCZ). At the start of El Niño events, convective storms are generated as the eastward-migrating pool of warm sea surface temperatures passes across northern Fiji waters, but as El Niño conditions fully develop, an equator-ward shift in the SPCZ away from the islands leads to prolonged dry conditions.

TROPICAL CYCLONE FLOODS

From 1970 to 2000, 40 tropical cyclones passed through Fiji waters. Individual cyclones deliver varying precipitation patterns according to the strength and longevity of the storms, the proximity of their tracks to land and the organization of the cloud bands. However, high magnitude rainfalls normally produce big flows in Fiji's rivers and large overbank floods are a frequent problem (Kostaschuk *et al.*, 2001), because the upper sections of river basins have rugged volcanic topography promoting a high

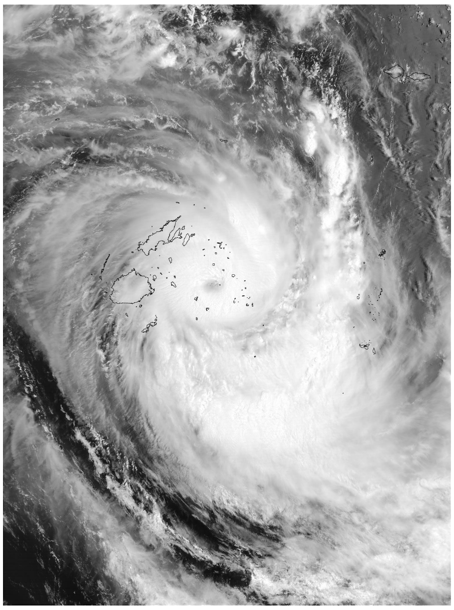

Fig. 2 Satellite image of TC Ami on 14 January 2003. The eye of the storm is passing through the Lau Group of islands in eastern Fiji on a south southeasterly track. Source: NOAA.

degree of hydrological short-circuiting. The coastal hinterlands on the north coast of Vanua Levu Island in northern Fiji are particularly vulnerable to flood hazard, especially around the main commercial centre of Labasa Town. This is because the north coast of Vanua Levu has many embayments, a configuration increasing the potential for storm surge inundation to combine with river floods (Terry & Raj, 1999). Also, three major river estuaries (Labasa, Qawa and Wailevu rivers) share the same bay and rise in the highest mountains with their basins facing the most common cyclone track direction. Therefore, exceptional orographic rainfalls are commonly produced by cyclones, and then rapidly converted into runoff, exacerbated by the widespread replacement of natural vegetation on lower slopes with sugar cane plantations.

Fiji's worst tropical storm this decade was Tropical Cyclone Ami (TC Ami) on 14 January 2003 (Fig. 2). The system originated as a tropical depression to the far east of Tuvalu on 10 January 2003 (Fiji Meteorological Service, 2003), but developed rapidly into an intense system with very destructive hurricane force winds. Travelling swiftly south to Fiji and driving enormous seas, the track crossed Vanua Levu Island, making landfall on the northeast peninsula shortly after 03:00, 14 January. At 12:00 the same day, Ami reached peak intensity when its centre was located in Fiji's Lau Islands group. Ten-minute average winds of about 200 km h^{-1} with gusts of 230 km h^{-1} were reported (NIWA, 2003). Ami travelled south southeast at 22 km h^{-1} as it left Fiji waters, maintaining hurricane intensity.

Torrential rainfall produced record floods in many Vanua Levu rivers and tragically 17 lives were lost. Large rainfalls were widespread; of 18 climate stations on Vanua Levu and nearby Taveuni Island, 16 locations recorded >100 mm of rainfall in 24 hours; of these, five stations received >200 mm. Maximum recorded rainfall was 311 mm at Vatuwiri station on Taveuni Island on the cyclone-facing coast beneath the highest mountain in the region (1241 m), therefore reflecting orographic effects.

Vanua Levu geology is made up of volcanic rock types, occurring mainly as lava flows, breccias and conglomerates. A chain of volcanic mountains aligned in a southwest to northeast orientation form a central highland spine and give a mountainous profile. The three tallest peaks above 900 m are towards the centre of the volcanic chain, south of Labasa Town. Most river networks drain generally northwest or southeast, controlled by the linear arrangement of the volcanoes. River watersheds are separated by narrow serrated interfluves and slope angles are steep, frequently approaching 30° or more. Upper river channels are steep and very bouldery; lower watershed areas have hilly terrain and flat alluvial terraces and flood plains in valley bottoms. The highlands are vegetated by natural rainforest, whereas the coastal hinterlands are used for commercial sugar cane cultivation.

Peak TC Ami discharges for eight main rivers on Vanua Levu island are presented in Table 1, surveyed by the Hydrology Division of the Fiji Public Works Department at their long-term gauging stations, soon after flood waters receded. Channel cross-sections and TC Ami flood heights at gauging stations in three rivers are drawn in Fig. 3 and compared to other floods in recent decades. The Nasekawa River in southern Vanua Levu had a phenomenal peak discharge of over 6100 $m^3 s^{-1}$, which destroyed the main highway bridge on the south coast at Bagata village. On the north coast, floods in the Labasa, Qawa and Wailevu rivers were all record-breaking events (2377, 1802 and 2118 $m^3 s^{-1}$ respectively). Heavy rainfall also led to many valley slopes failing in landslides, some of which temporarily dammed rivers but subsequently failed. The emptying of large volumes of water from all three rivers, at the same time, to the same coastal plain, further combined with a strong storm surge felt along the north coast of Vanua Levu, to cause severe inundation of 3–4 m depth over a wide area. Huge quantities of sediments, deposited by swollen rivers, ruined sugar cane farms and extensive infrastructural damage was suffered by Labasa Town (Fig. 4). Domestic water supply was contaminated and disrupted, forcing the Fiji Government to transport potable water from mainland Viti Levu island to avoid outbreaks of disease.

Table 1 Peak river discharges on Vanua Levu island, produced by TC Ami on 14 January 2003.

River	Catchment area (km^2)	Discharge ($m^3 s^{-1}$)
Nasekawa	104	6139
Labasa	86	2377
Wailevu	77	2118
Qawa	38	1802
Dreketi	128	996
Wainikoro	45	676
Nakula	16	559
Bucaisau	80	447

ENSO AND HYDROLOGICAL DROUGHT

At the inter-annual timescale, the El Niño Southern Oscillation (ENSO) is our planet's most powerful climatic phenomenon (Hilton, 1998). During strong negative ENSO phases (El Niños), the western Pacific suffers prolonged rainfall failure. Many

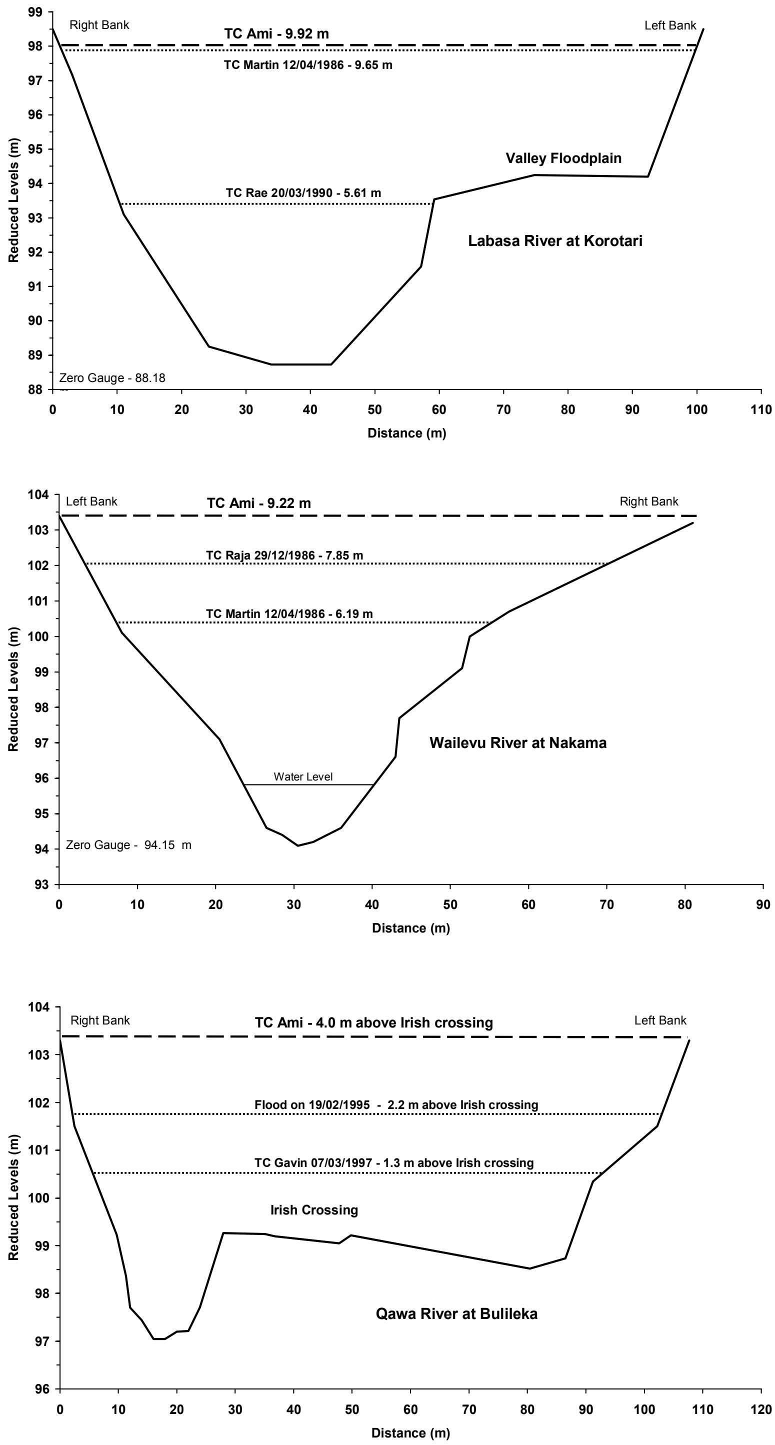

Fig. 3 Maximum flood heights produced by TC Ami in three main rivers on Vanua Levu island. Source: Fiji PWD Hydrology Division unpublished flow records.

commentators described the 1997–98 El Niño induced drought in Fiji as a 1-in-100 year event. Although tropical storms gave large rainfalls in early 1997, by mid-1997 the situation had deteriorated with strengthening El Niño conditions and low monthly rainfalls (Fiji Meteorological Service, 1997). The SPCZ, normally the main moisture

Fig. 4 Flood waters in Labasa Town on the north coast of Vanua Levu island, generated by the coincidence of overbank flows of the Labasa and Qawa rivers with storm surge inundation by the sea.

producing weather system in the early wet season, was notably absent. Sub-tropical anticyclones and persistent high pressure ridges dominated conditions, giving very little precipitation. Smaller outer islands and western districts of Viti Levu island were severely drought stricken by early 1998 and the effects continued until the end of the 1998 dry season when the SPCZ drifted southwards towards the main Fiji group, and associated weak low pressure troughs brought frontal rainfall which finally broke the drought.

When examining the severity of drought in Fiji, the flow behaviour of streams provides useful information to supplement rainfall data from climate stations. A big drawback with rainfall data is that they only show the receipt of moisture at single points in the landscape. Accurate spatial interpretation of this information is difficult because rainfall in the humid tropics can be extremely localized. In contrast, stream discharge reflects (antecedent) precipitation over a whole catchment, and incorporates the influence of physiographic, geological and hydrometeorological characteristics of the area. This makes streamflow a better indication of water resource availability, especially because in rural parts of Fiji any rainfall collected by roof catchments lasts only for the first few weeks of a dry spell, and thereafter the population relies heavily on streams for domestic needs and watering livestock.

In the Pacific region there are strong ENSO controls on stream behaviour through influences on regional climatic patterns. In recent years, hydrological studies have explored links between ENSO and various parameters of river flow, including seasonality and extremes (e.g. Chiew *et al.*, 1998; Moss *et al.*, 1994, Waylen & Laporte, 1999). Indications have emerged in Costa Rica, eastern Australia, New Zealand and parts of the Pacific USA mainland, for example, that good relationships between streamflow and SOI, or other ENSO measures such as sea surface temperatures, can be established (Kahya & Dracup, 1993; Moss *et al.*, 1994; Cayan *et al.*, 1999; Krasovskaia *et al.* 1999).

During El Niño induced droughts, rivers in the rain-shadowed northwest of Fiji's high islands experience critically low stream baseflows. The Ba River in the north of Viti Levu is Fiji's third largest river system covering 930 km^2 and is the major dry zone fluvial system. Savannah grassland vegetates the steep highland terrain, whereas

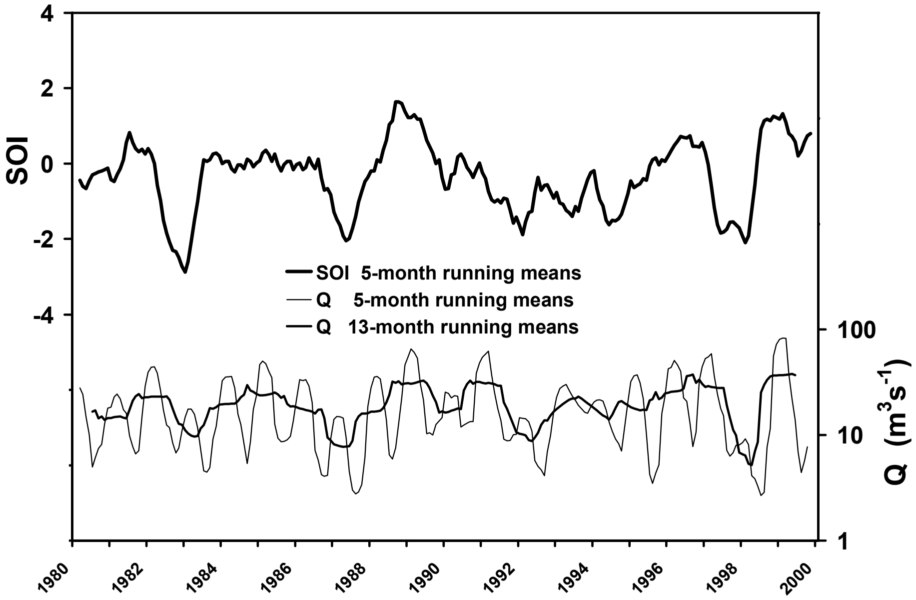

Fig. 5 Comparison of patterns in SOI and Ba River flow (*Q*) 1980–2000.

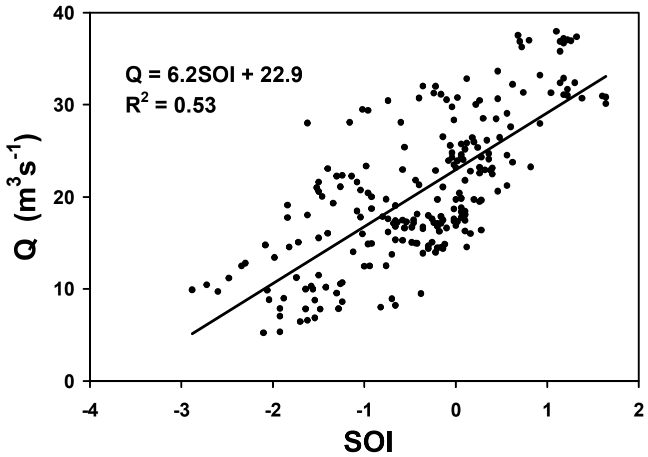

Fig. 6 Correlation between 13-month running means of Ba River (*Q*) and 5-month running means of SOI with a 2-month lag.

the more gentle coastal slopes have sugar cane plantations. Here we compare SOI temporal patterns with the mean river discharge (*Q*) (Fig. 5) to gain a better understanding of the strength of the relationship. Difficulties arise when comparing SOI and monthly discharge because of significant seasonality influences on river behaviour, so poor correlations were derived between SOI *vs* monthly *Q* (r = 0.17), prior 3-month mean of SOI *vs* monthly *Q* (r = 0.21), SOI *vs* *Q* for the month with the lowest flow each year (r = 0.18), and lowest monthly SOI in year *vs* lowest monthly *Q* in year (r = 0.23). However, if flow seasonality is removed by plotting 13-month running means, low flow trends in the Ba River show good correspondence with SOI values, although lagging behind by approximately two months ($r = 0.73$, $P > 0.001$, Fig. 6).

CONCLUSIONS

Floods and droughts in Fiji are serious hydrological hazards because of their impacts on both natural and human environments, causing loss of life, damage to infrastructure, the ruin of subsistence and commercial agriculture, and deleterious effects on public health. The north coast of Vanua Levu island is particularly vulnerable to floods, owing to its geomorphological characteristics and because most tropical cyclones approach from northern Fiji waters. During TC Ami in mid-January 2003, the mountainous volcanic terrain rapidly transferred very large rainfalls into river channels, generating record breaking discharges. In the Labasa area, three rivers simultaneously delivered large amounts of water to the same coastal hinterland, at the same time as cyclone generated storm surge. This caused widespread inundation, over 4 m in some areas. Although it remains difficult to predict the occurrence of tropical cyclones in the South Pacific, the experience of TC Ami encourages the prioritization of improved hazard management on Vanua Levu island, to avoid loss of life and to mitigate the difficult socio-economic burden caused by flood impacts.

This study also examined the relationship between SOI values and monthly flows in the major Ba River in the dry zone of Fiji's main island Viti Levu, because an improved understanding of ENSO induced anomalous river behaviour is important for water resources planning. Critically low base flows lag behind SOI by approximately two months. Climate variability in the Pacific region may increase in the future with a shift to more sustained El Niño conditions. SOI values, in conjunction with other climatic parameters, should assist in drought preparedness programmes on Viti Levu, although a small and resource-limited island nation like Fiji may require international aid and project assistance in order to implement suitable adaptation options (World Bank, 2000).

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