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Sensitivity of Kelani streamflow in Sri Lanka to ENSO

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Abstract:

As part of an effort to demonstrate the use of climate predictions for water resources management, the El Niño/Southern Oscillation (ENSO) influences on stream flow in the Kelani River in Sri Lanka were investigated using correlation analysis, composite analysis and contingency tables. El Niño (warm phase of ENSO) was associated with decreased annual stream flow and La Niña (cold phase of ENSO) with increased annual flows. The annual stream flow had a negative correlation with the simultaneous ENSO index of NINO3·4 that was significant at the 95% level. This negative correlation is enhanced to a 99% level if the aggregate January to September or the April to September stream flow alone were considered. Although, there is little correlation between ENSO indices and stream flow during the October to December period, there is a high correlation between rainfall and NINO3·4 ($r = 0{\cdot}51$, significant at the 99% level). Therefore ENSO based rainfall predictions can be used along with a hydrological model to predict the October to December stream flow. This study demonstrates the viability of using ENSO based predictors for January to September or April to September stream flow predictions in the Kelani River. The October to December stream flow may be predicted by exploiting the strong relationship between ENSO and rainfall during that period. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS Sri Lanka; Kelani; stream flow; predictions; ENSO; El Niño; hydrometeorology

INTRODUCTION

The El Niño/Southern Oscillation (ENSO) phenomena is now recognized as a primary mode of seasonal climatic variability, particularly in the tropics (Ropelewski and Halpert, 1987). It has become possible to forecast ENSO phenomenon with some skill up to nine months in advance (Cane and Zebiak, 1985). Therefore any association between ENSO and stream flow can be used for a prediction scheme to aid water management. Sensitivity of stream flow to ENSO has been investigated for a number of rivers (Simpson *et al*., 1993; Amarasekera *et al*., 1997; Uvo and Graham, 1998; Wang and Eltahir, 1999) and a comprehensive review of these and other efforts is provided in Dettinger *et al*. (2000).

One of the regions where a significant ENSO influence on rainfall and temperature has been reported is Sri Lanka (Rasmussen and Carpenter, 1983; Ropelewski and Halpert, 1987; Suppiah, 1997). In this paper, the ENSO influence on stream flow of one of the major rivers in Sri Lanka, the Kelani (Figure 1), is investigated.

The Kelani originates at an altitude of 2400 m and garners rainfall on the western slopes of the central mountain ridge (Zubair, 2002b) and discharges to the sea 144 km downstream at Colombo. The annual rainfall in Sri Lanka is highly variable, ranging from 500 mm to 6000 mm (Figure 1). The highest annual rainfall is in the upper catchment of the Kelani River. Of the annual precipitation of 8200 Million Cubic Meters (MCM) in the basin of 2292 km^2, approximately 3300 MCM is discharged to the sea. For the period from 1949 to 1993, the stream flow at Glencourse (Figure 1) has an average of 4565 MCM and a standard deviation of 895 MCM with a minimum of 2655 MCM in 1984 and a maximum of 6556 MCM in 1976.

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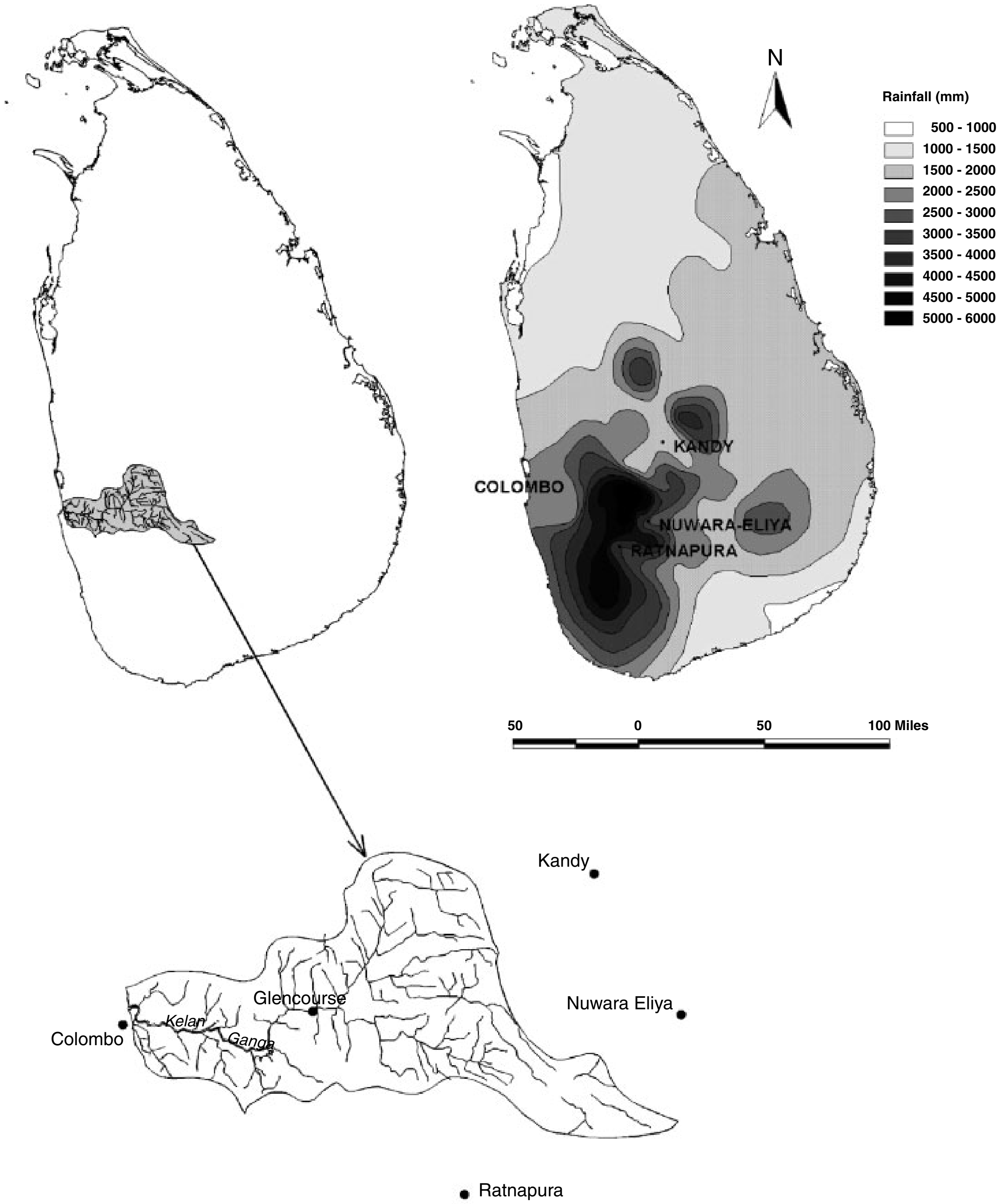

Figure 1. Top left: map of Sri Lanka showing the Kelani river basin. Bottom: expanded version of the Kelani River basin. The rainfall and stream flow stations used in this study are shown. Top right: the annual rainfall climatology for the period from 1960 to 1990 computed from 174 rainfall stations on the island

The Kelani discharges to the sea at the commercial capital city of Colombo. It was in response to the abundant availability of water that Colombo was established as a Portuguese colonial outpost in the early sixteenth century (Muller, 1995). Over time it has grown into a large metropolis with a population of four million people (Department of Census and Statistics, 2000). A large fraction of this population is supplied with water from the Kelani River.

Since 1953, two reservoirs and five power stations (aggregate capacity of 335 MW) have been built to harness hydro-electricity (Ceylon Electricity Board, 1989). The Kelani hydropower plants provide 38% of the hydro-electricity that is generated in Sri Lanka. Two hundred MCM of river water is tapped annually for municipal water supply for the Colombo metropolitan area alone. Sri Lankan rivers have experienced a declining stream flow in the past two decades, which has been attributed to changing land use (Wickramagamage, 1997). This decline exacerbates the stress on the water supply.

In addition, heavy rains resulting in a rapid rise in Kelani stream flow poses a frequent flood hazard for Colombo (National Science Foundation, 2000). Hence, stream flow variations have profound impacts and skilful stream flow predictions would be useful for energy planning, flood preparedness and municipal water budgeting.

The rainfall climate of Sri Lanka is characterized by a bimodal distribution (Figure 2) with peaks around May and September as a result of the thunderstorms associated with the location of the Inter-tropical Convergence Zone (ITCZ) over Sri Lanka. In addition, monsoonal influences and cyclonic storms from the Bay of Bengal contribute to high rainfall from October to December. The western hillslopes also receive considerable rainfall from orographic rainfall from June to September when strong westerly winds prevail.

The climate of Sri Lanka is modulated during ENSO extremes owing to the alteration in intensity and location of the large-scale equatorial circulation system referred to as the Walker cell (Allan *et al*., 1996). The extreme phases of the ENSO phenomenon associated with warm and cold sea surface temperatures in the equatorial eastern Pacific Ocean are referred to as El Niño and La Niña respectively. The rainfall of Sri Lanka is diminished from January to March and from July to August (Zubair, 2002a) during El Niño episodes, owing to large-scale subsidence over the central Indian Ocean region (Krishna Kumar *et al*., 1999).

However, the October to December rainfall is enhanced during El Niño (Rasmussen and Carpenter, 1992). The zone of subsidence that was located over Sri Lanka at the end of the summer (Suppiah, 1996, 1997) is shifted northwards, towards India. As a result, during the autumn there is a zone of convergence over Sri Lanka leading to enhanced rainfall. This ENSO–rainfall relationship is important as the October to December

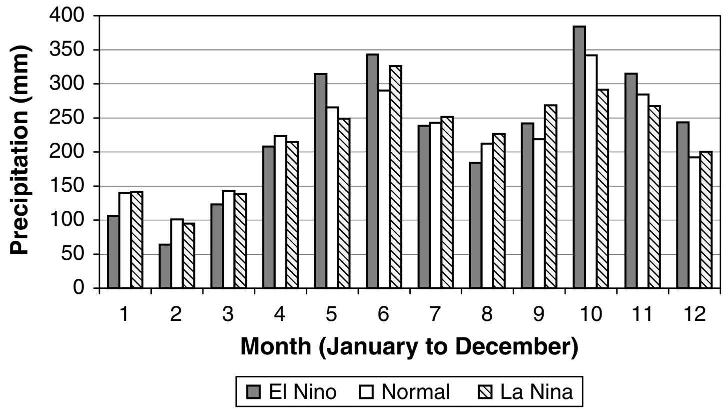

Figure 2. The composite rainfall climatology of the Western slopes region during El Niño, La Niña and normal phases. The Western slopes rainfall index is constructed as the average of the rainfall at Kandy, Ratnapura and Nuwara Eliya. This rainfall is averaged during periods when each of the three ENSO phases was prevalent. The ENSO phases were identified following Trenberth (1997)

period accounts for one-third of the annual rainfall. It also irrigates during the main rice crop season and is immediately prior to a relatively dry spell from January to mid-April.

The ENSO influence on July to August and October to December rainfall during La Niña is in the opposite sense of that during El Niño (Suppiah, 1996, 1997; Zubair, 2002a). However, from January to March, La Niña conditions also are associated with a decline in rainfall, although not as much as that for El Niño conditions.

The ENSO rainfall and stream-flow data and methods of analyses are described next. Thereafter, the analyses of the ENSO influences on rainfall and stream flow are presented. Finally, the main conclusions are summarized and their implications are discussed.

DATA AND METHODS

ENSO data

The sea-surface-temperature (SST) based indices of NINO12, NINO3, NINO3·4 and NINO4 were used as indices for ENSO. The SST (Kaplan *et al.*, 1998) in various equatorial Eastern Pacific Ocean regions (indicated in brackets) were averaged for each index: NINO12 (80 °W–90 °W, 10 °S to the Equator), NINO3 (120 °W–150 °W, 5 °S to 5 °N), NINO3·4 (120 °W–170 °W, 5 °S to 5 °N) and NINO4 (150 °W–180 °W, 5 °S to 5 °N) (Allan *et al.*, 1996). The atmospheric pressure based 'Southern Oscillation Index' (SOI) was obtained following Ropelewski and Jones (1987).

The three ENSO phases of El Niño, La Niña and normal are identified following Trenberth (1997). El Niño, La Niña and normal phases are taken to prevail when the 5-month running mean of NINO3·4 is above 0·4 °C, below −0·4 °C or in between these two limits respectively.

Rainfall data

The Kelani catchment lies within the climatically homogeneous 'Western slopes' region identified by Puvaneswaran and Smithson (1993). There are no WMO/Department of Meteorology stations within the upper Kelani catchment. As an alternative, rainfall at three stations that are well distributed in the wider Western slopes region were chosen (Kandy—7° 20′ N, 80° 38′ E, 477 m a.s.l; Nuwara Eliya—6° 58′ N, 80° 46′ E, 1895 m a.s.l; Ratnapura—6° 40′ N, 80° 25′ E, 34 m a.s.l) (Figure 1). All three stations and the Kelani basin are located on the windward side (from April to September) of the Western slopes. From late October to mid-March, all three stations and the Kelani basin are on the leeward side. Thus the rainfall at the three stations is representative of that in the Kelani catchment at Glencourse for all seasons. A representative rainfall index for the Western slopes was constructed by averaging the rainfall of these stations. Monthly rainfall records are available for these three stations from 1869, however, only the data from 1948 to 1993 were used in the analysis in keeping with the more limited duration of stream flow data that were available.

Streamflow data

Monthly stream flow records for the Kelani River are available at 15 stream-flow measuring stations from the Sri Lanka Department of Irrigation. The station that has the longest record (from 1948 to 1993) is at Glencourse (6° 58′ N, 80° 10′ E, 32 m a.s.l, 1463 km^2 catchment) where the Kelani descends to the lowlands of the island. The data at Glencourse were consistent with those at neighbouring gauge stations.

Two reservoirs were constructed in the higher reaches of the Kelani starting in 1953 as storage for hydroelectricity generation stations. These reservoirs have a small storage capacity of 169 MCM and a drainage area of 236 km^2, which is only 10% of the Kelani basin. The impacts of reservoir management on stream flow at Glencourse may be reasonably overlooked for this analysis given that the reservoirs affect only 10% of the Glencourse catchment.

Seasons in Sri Lanka

There is year round rainfall in Sri Lanka and there is no clear-cut means of demarcating the seasons. The periods of highest rainfall in the whole island last from late April to June and mid-September to mid-January. One marker of seasonality is the change in wind direction from north-easterly to south-westerly associated with the monsoon system (Zubair, 2002b). Although these monsoon periods may identify the period with strong winds, they do not identify the periods of similar rainfall patterns particularly well.

Most appropriate for the study of rainfall and stream flow is the traditional demarcation of seasons based on the rice cultivation seasons. The *Maha* season is from October to March and the *Yala* is from April to September (Zubair, 2002a). Both seasons may be divided into an early half, which is relatively wet, and a late half, which is relatively dry. Although over most of Sri Lanka, late *Maha* and *Yala* are dry, there is significant orographic rainfall during late *Yala*. The breakdown that has been described, is also consistent with ENSO influence as the following aggregation of months have similar ENSO influence: JFM, M, JA and OND (Zubair, 2002a). Therefore, all further analysis is carried out on quarterly sums of monthly rainfall and stream flow data, namely for JFM (late *Maha*), AMJ (early *Yala*), JAS (late *Yala*) and OND (early *Maha*).

Correlation analysis

Correlation analysis was used to identify relationships between ENSO indices and stream flow or rainfall. The exact variables that were correlated are detailed later in relevant sections. The Pearson correlation coefficient, which is a linear measure, was used (Press *et al*., 1992). A correlation was taken to be significant when the hypothesis that there was no correlation between two time-series was unlikely with a probability of 95% and highly significant when the probability was 99%. The analyses were compared with robust methods such as ranked correlation to check for non-linear relationships.

Contingency tables and Heidke skill scores

A contingency table may be constructed to identify the influence of ENSO on a variable such as stream flow based on historical data (Wilks, 1995). Such data provide an association between occurrences of particular ENSO phases and stream-flow conditions. The ENSO phases may be segregated depending on the prevalent value for an ENSO index in terciles, as El Niño, normal and La Niña. Similarly, the stream flow may be segregated in terciles representing 'below-normal', 'near-normal' and 'above-normal' flow. The occurrences of ENSO phases and stream-flow conditions in different ENSO/stream flow tercile combinations may be tabulated. Such a table provides a simple representation of association between ENSO and stream flow.

The Heidke skill score (Wilks, 1995) is a measure of forecast skill that is widely used when the forecasts and corresponding observations are expressed in categories such as below-normal, near-normal and above-normal. The score is based on the number of forecasts where the category with the largest forecast probability turned out to be correct. The skill (S) is given by $S = 100(C - E)/(N - E)$, where C is the number of correct forecasts, E is the number of correct forecasts expected by chance and N is the total number of forecasts. With three categories, the formula reduces to $S = 150\ [(C/N)—(1/3)]$. An all-correct forecast results in a score of 100, whereas a forecast with as many correct as expected by chance scores 0. The values may be negative too. The Heidke score, although simple, has its drawbacks—it does not penalize two category errors (that is the occurrence of below-normal when above-normal was predicted and vice versa) or discriminate among probabilistic forecasts for different categories.

RESULTS

Insights into the correlations between ENSO and stream flow are obtained by considering the simultaneous correlation between ENSO and rainfall. The latter is described further in the next section and the former in the next but one section.

Analysis of ENSO influences on rainfall in the Western slopes region

The ENSO relationship with rainfall in the Western slopes region was distinguished (Figure 2) by conditionally averaging the monthly rainfall when the El Niño, La Niña or normal ENSO phases prevailed. There is a positive relationship between rainfall and ENSO from October to December, and the relationship is negative and weaker from January to April and July to September. During May and June the ENSO–rainfall relationship is weakly positive. The ENSO–rainfall relationships during the first three-quarters of the year are too weak (Table I) to obtain predictability. However, if the ENSO–rainfall relationship in the period from January to September is considered, then the predictability is improved.

The aggregate January to September rainfall shows a correlation ($r = -0{\cdot}51$) with concurrent NINO3·4 between 1948 and 1993 that is significant at the 99% level. The January to September rainfall shows an 11% decrease on average during El Niño episodes.

The October to December rainfall shows a correlation of 0·42 with the NINO3·4 index from 1948 to 1993, which is significant at the 99% level (Table I). The October to December rainfall shows a 15% increase during El Niño episodes and a 7% decline during La Niña Events.

Correlations with different ENSO indices gave similar results. The only exception was NINO12, which, although generally producing results similar to the other indices, gave a weaker relationship with OND rainfall and a stronger relationship with JFM rainfall. NINO12 is set in the far Eastern Pacific Ocean and is the least representative of the indices for the broad-scale ENSO phenomenon.

Analysis of ENSO influence on stream flow in the Kelani

The ENSO relationship with the Kelani stream flow at Glencourse during El Niño, La Niña and normal phases was distinguished by conditionally averaging the monthly stream flow in periods where each phase prevailed (Figure 3). The stream flow during El Niño episodes is lower for the entire period from January to September. The concurrent ENSO–stream-flow correlation is insignificant between October and December, unlike that between ENSO and rainfall (Table II).

The reasons for a disparity between ENSO influences on precipitation and stream flow could include (i) precipitation freezing in a season and being released as snow-melt subsequently in a season of different ENSO influence, (ii) different ENSO signals upstream of the stream-flow gauging station coupled with long stream-flow travel time, (iii) storage in underground reservoirs, (iv) seasonality in evaporation or (v) groundwater recharge–discharge mechanisms (Dettinger and Diaz, 2000). Of these factors, only the last applies to the Kelani during the October to December season. There is no snow in Sri Lanka, no known underground reservoirs, no marked variation in seasonality of evaporation (Piper *et al*., 1994) and the upper catchment is in a region of homogeneous ENSO influence (Suppiah, 1996). In addition the travel time for water down the entire length of the river is only a few days (Arumugam, 1969).

Table I. Seasonal breakdown of rainfall in the Western slopes region of Sri Lanka based on average rainfall records for Nuwara Eliya, Ratnapura and Kandy from 1869 to 1998. The correlations of rainfall with ENSO indices and rainfall for the same period are also shown. For the record from 1948 to 1993 the significance levels at 99% and 95% are 0·38 and 0·29 respectively. Correlations that are significant at 95% are underlined

Characteristic	Season				Annual Total	January to September
	JFM	AMJ	JAS	OND		
Mean Rainfall (mm)	319	764	563	827	2473	1646
Standard Deviation (mm)	118	163	169	180	285	290
Correlation with NINO12	<u>−0·40</u>	−0·07	−0·23	0·27	−0·18	<u>−0·41</u>
Correlation with NINO3	−0·20	0·18	−0·05	<u>0·52</u>	−0·18	<u>−0·47</u>
Correlation with NINO3·4	<u>−0·29</u>	0·10	−0·06	<u>0·51</u>	−0·20	<u>−0·50</u>
Correlation with NINO4	−0·25	0·21	−0·10	<u>0·45</u>	−0·23	<u>−0·48</u>
Correlation with SOI	0·18	−0·10	0·21	<u>−0·44</u>	0·12	<u>0·41</u>

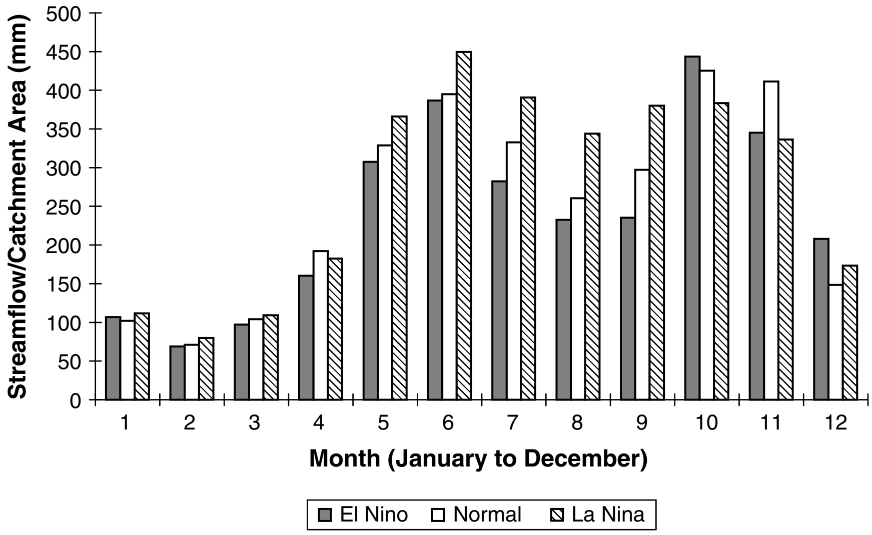

Figure 3. The composite stream flow hydrograph at Glencourse along the Kelani River during the El Niño, La Niña and normal phases. The stream flow is averaged during periods when the particular ENSO phases prevailed. The ENSO phases were identified following Trenberth (1997)

Table II. Seasonal breakdown of Kelani stream flow at Glencourse based on rainfall records from 1948 to 1993. The correlations of stream flow with ENSO indices for the same period are also shown. Significance levels for correlation at 99% and 95% are 0·39 and 0·30 ($n = 46$). Correlations that are significant at 95% are underlined

Characteristic	Season				Annual Total	AMJJAS	JFMAMJJAS
	JFM	AMJ	JAS	OND			
Mean Discharge (MCM)	413	1316	1361	1448	4665	2677	3089
Standard Deviation (MCM)	145	408	483	439	895	685	727
Correlation with NINO12	−0·32	−0·25	−0·35	−0·03	−0·40	−0·40	−0·51
Correlation with NINO3	−0·10	−0·25	−0·36	0·11	−0·47	−0·42	−0·56
Correlation with NINO3·4	−0·10	−0·24	−0·36	0·17	−0·41	−0·41	−0·53
Correlation with NINO4	−0·11	−0·19	−0·46	−0·16	−0·42	−0·46	−0·54
Rank Correction with NINO4	−0·21	−0·17	−0·46	0·31	−0·33	−0·46	−0·49
Correlation with SOI	0·11	0·05	0·47	0·21	0·39	0·37	−0·50

Thus, the reason why the ENSO–stream-flow correlation in OND during El Nino is insignificant is because typically the ground conditions during summer are dry and groundwater recharge is diminished. Thus even though there is enhanced rainfall in OND, the stream-flow signal does not respond immediately. It takes a month or two for the stream flow to really pick up, but by December the stream flow has indeed increased.

Given the strong relationships with the January to September rainfall, the rest of the analysis is restricted to the aggregate January to September stream flow.

The annual stream flow at Glencourse shows a high correlation ($r = -0{\cdot}37$) with the annual NINO3·4 from 1948 to 1993 (Table II) that is significant at the 95% level. The aggregate January to September stream flow (Figure 4) shows a correlation ($r = -0{\cdot}53$) with NINO3·4 that is significant at the 99% level. This correlation increases to 0·65 for the period 1972 to 1993. The average January to September stream flow under the El Niño phase is 17% less than that during the La Niña phase.

A contingency table is presented (Table III) showing the distribution of occurrence of aggregate January to September stream flow in tercile categories ('below-normal', 'near-normal' and 'above-normal') during

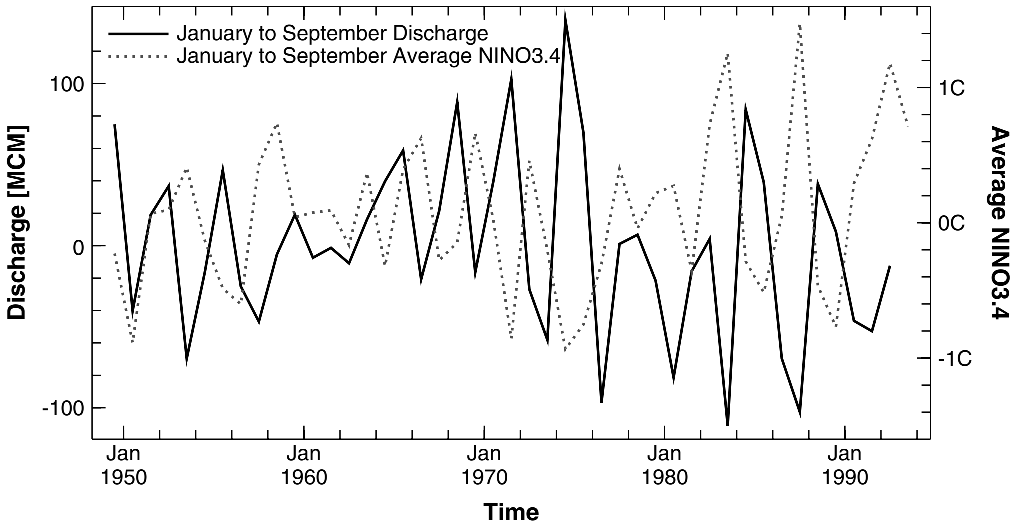

Figure 4. The time-series of aggregate January to September stream flow (discharge) anomaly at Glencourse and the concurrent average January to September NINO3·4 index are shown

Table III. Contingency table (as described in text) for the ENSO association with January to September Kelani stream flow at Glencourse between 1948 and 1993. The stream flow terciles are defined in the following manner: 'Below-normal', Stream flow < 2815 MCM; 'Near Normal', 2815 MCM < stream flow < 3290 MCM; 'above-normal', stream flow > 3290 MCM. El Niño, normal and La Niña phases are identified following Trenberth (1997) as seasons where the average January to September NINO3·4 values were greater than 0·4 °C, in between 0·4 °C and −0·4 °C and less than −0·4 °C respectively

NINO3·4	Streamflow tercile		
	Below-normal	Near-normal	Above-normal
El Niño (>0·4 °C)	7	5	1
Normal	6	7	8
La Niña (<−0·4 °C)	2	1	6

periods when El Niño, La Niña and normal phases of ENSO prevailed. The contingency table shows that during El Niño events, the 'below-normal' category prevails but during La Niña, the 'above-normal' category prevails.

A forecast based on ENSO alone would associate El Niño with below-normal stream flow, the normal ENSO phase with near-normal stream flow, and La Niña with above-normal streamflow. This turns out to be correct during 20 years out of 42 (Table III). The Heidke skill score for this sequence is 21, which shows useful skill. The frequency of two-category errors (i.e. above-normal occurring when below-normal was forecast or vice versa), which could be damaging, is small at 7%.

CONCLUSIONS AND DISCUSSION

This work has distinguished a clear relationship between ENSO and rainfall and ENSO and stream flow in the Kelani River basin. El Niño conditions are associated with lower annual rainfall and stream flow and La Niña with the converse. This association is more pronounced when the rainfall and stream flow for January to September or the April to September stream flow alone are considered. In contrast to this relationship, the rainfall from October to December increases during the El Niño phase and decreases during the La Niña phase. However, the ENSO influence on October to December stream flow is ambiguous. This ambiguous influence is attributable to dry soil conditions and diminished groundwater recharge, as is typical during El Niño summers, masking the influence of increased rainfall on stream flow during autumn. This example shows that although the seasonal ENSO relationship with precipitation provides clues as to its relationship with stream flow, it is not necessarily alike, especially in river basins with multiple types of ENSO influences.

The relationship between the ENSO indices, rainfall and stream flow are significant from January to September. In addition, a skilful prediction can be obtained for April to September stream flow based on ENSO indices, and the strong relationship between ENSO and rainfall can be used in a hydrological model to obtain predictions for OND stream flow as well. Further investigations of influences of other climatic precursors, such as Indian Ocean conditions and Eurasian snow cover, on stream flow and rainfall should contribute to an even more reliable prediction scheme.

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