Predictability of stream flow and rainfall based on ENSO for water resources management in Sri Lanka

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Summary We investigate the viability of using El Niño–Southern Oscillation (ENSO) and sea surface temperature (SST) data to predict seasonal streamflow for one of the major rivers in Sri Lanka, the Kelani, using correlation analysis, contingency tables, and principal component analysis. The agricultural seasons in Sri Lanka are Yala (April–September) and Maha (October–March). The correlation between the Kelani River streamflow during Yala and ENSO indices ($r = -0.41$) is significant at 99% level. In addition, the Kelani streamflow during Yala has a correlation with the Central Indian Ocean SST ($r = -0.40$) that is also significant at the 99% level. The first principal component of the Indo-Pacific Ocean SST is reminiscent of the SST associated with the ENSO mode. A prediction scheme based on this mode for the streamflow during Yala has a skill characterized by a correlation of 0.5 in a cross-validated mode.

The prediction of streamflow during Maha is best carried out separately for the two halves of the season. During the El Niño phase, the rainfall during Maha is enhanced during the first half of the season (October–December) and diminished in the second half (January–February). Rainfall rather than streamflow has a better relationship with ENSO from October to December. During the second half of the Maha season, rainfall declines with both warm and cold ENSO phases and any prediction scheme has to take into account this non-linear relationship. Overall, useful skill for seasonal streamflow predictions has been demonstrated for the Yala season and skill for seasonal rainfall predictions for the first and second half of the Maha season has been elucidated.

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Introduction

The principal global climate teleconnection of El Niño–Southern Oscillation (ENSO) affects hydrology in much of
the tropics through its impacts on the variables such as rainfall, temperature and evaporation (Dettinger and Diaz, 2000). These ENSO influences extend to Sri Lanka rainfall (Rasmusson and Carpenter, 1983; Ropelewski and Halpert, 1987). Sensitivity of streamflow to ENSO has been investigated for a number of rivers in all continents and several reviews are available (Kiem and Franks, 2001; Dettinger et al., 2000 and Chiew and McMahon, 2002). In the South Asian region, relationships have been identified between streamflow and ENSO in India and Bangladesh (Chowdury and Ward, 2004; Whitaker et al., 2001), Nepal (Shrestha and Kostaschuk, 2005) and Sri Lanka (Zubair, 2003b,c).

Studies on the ENSO impacts in Sri Lanka are important as it presents information about the low-latitude region of South Asia which experiences rainfall throughout the year. The phases of the ENSO phenomena associated with warmer and colder than normal sea surface in the equatorial Central and Eastern Pacific Ocean are referred to as El Niño and La Niña, respectively. The rainfall of Sri Lanka and India is diminished during El Niño episodes in the boreal summer due to large-scale subsidence over the Central Indian Ocean region (Kumar et al., 1999) and enhanced from October to December (Rasmusson and Carpenter, 1983; Ropelewski and Jones, 1987; Suppiah, 1996, 1997).

The climate of Sri Lanka is modulated during ENSO extremes due to the alteration in intensity and location of the large-scale equatorial circulation system associated with it referred to as the Walker cell (Allen et al., 1996). From April to September, rainfall over Sri Lanka is relatively lower during El Niño similar to anomaly patterns over the Indian peninsula. During the October–December season, the eastward displacement of the Walker cell in the Indian Ocean is such that Sri Lanka receives increased rainfall anomalies (Zubair et al., 2003a, Zubair and Ropelewski, 2006). This relationship is important as the October–December period accounts for a third of the annual rainfall.

Here we investigate the possibility of using ENSO for the management of water resources in the Kelani River in Sri Lanka (Fig. 1). The Kelani is the second largest river in Sri Lanka by volume of discharge although it is only the sixth largest in watershed size (Arumugam, 1969). The highest annual rainfall in Sri Lanka is observed in the upper reaches of the Kelani catchment and the areal average annual rainfall is 3880 mm. Two reservoirs and five hydropower plants have been built to utilize the flow for hydropower generation. These power plants generate 38% of the total hydropower production in Sri Lanka (Siyambalapitiya and Samarasinghe, 1993). The Kelani feeds the municipal and industrial water supply to 2.2 million people in Colombo, from reservoirs on tributaries that join the main Kelani River below Glencourse gorges (Fig. 2). The lowland areas downstream of Glencourse gorges are frequently subjected to flooding. The other major rivers in Sri Lanka, Mahaweli, Kalu and Walawe, share boundaries with the Kelani in the upper catchment and interpretations from this work is likely to have some bearing on the other rivers.

The agricultural seasons in Sri Lanka last from April to September (Yala) and October to March (Maha) (Zubair, 2002). Choices are made at the start of the season as to what extent of land is to be cultivated, and whether more irrigation intensive rice crops should be cultivated. Hence rainfall and streamflow predictions are needed at the start of these seasons. Previously, the ENSO influence for the January–September streamflow in Sri Lanka was reported (Zubair, 2003b,c). However, this period does not match with the seasons of interest to water managers and agricultural managers who take seasonal planning decisions in April and September for the April–September and October–March cultivation seasons. Here we seek to establish the relationships between ENSO and streamflow or rainfall for Yala and Maha, and to assess the potential for ENSO based predictions for water management.

Data and methods

Monthly sea surface temperatures, rainfall and streamflow data for 1950–2000 were used.

SST and ENSO data

The monthly sea surface temperature (SST) (Kaplan et al., 1998) is available at http://iridl.ldeo.columbia.edu/SOURCES/.KAPLAN/.EXTENDED/.v2/.ssta/ from 1856. The

The three ENSO phases of El Niño, La Niña and Neutral are identified as seasons when the NINO3.4 was above 0.4°C, below 0°C or in between these two limits, respectively (Trenberth, 1997). The atmospheric pressure based index of “Southern Oscillation Index” (SOI) was obtained following Ropelewski and Jones (1987).

Rainfall data

The Kelani catchment lies within a climatically homogeneous Western hill slopes region as identified by Puvaneswaran and Smithson (1993). There are 16 stations within or close to the Kelani catchment at government hospitals, railway stations and tea estates (Zubair, 2004). The rain gauges are provided by the Department of Meteorology, and the Department personnel inspect these gauges, archive the data and undertake quality control of it. We have undertaken further quality tests for this data – identifications of outliers, cross checks for extreme values, checks for drifts in the data and cross-correlation analysis. Based on these analyses we decided to use only 10 of these stations that had good coverage of the basin (Fig. 2). A monthly catchment rainfall index was constructed for Glencourse by areally averaging rainfall observations of these 10 stations.

We compared the results with monthly rainfall observations at three Sri Lanka Department of Meteorology stations that are distributed in the wider Western hill slopes region (Kandy (7°20′N, 80°38′E, 477 m above sea level (a.s.l.)), Nuwara Eliya (6°58′N, 80°46′E, 1895 m a.s.l), and Ratnapura (6°40′N, 80°25′E, 34 m a.s.l)) (Fig. 2). A representative rainfall index for the Western Hill slopes region was constructed by averaging the rainfall of these stations. The catchment rainfall has a similar seasonality as the regional rainfall (Fig. 3a). The catchment rainfall is fractionally greater than the regional rainfall, as it is more compactly located in a region with the highest rainfall over Sri Lanka from March to November.

Streamflow data

The Kelani river originates in the central hills at Kirigalpotha mountain range (2420 m a.s.l.) and discharges to the sea 144 km downstream at Colombo. The upper reaches of the basin are covered with tea plantations and forested lands whereas the middle and lower reaches have rubber and rice cultivation. The soil type in the basin is typically red-yellow podzolic soil with soft and hard laterite (Panabokke, 1996).

Streamflow records for the Kelani are available at 15 streamflow measuring stations from the Sri Lanka Department of Irrigation. The station that has the longest record is at Glencourse (6°58′N, 80°10′E, 32 m a.s.l., 1463 km² catchment) where the Kelani descends to the lowlands. We obtained records from 1948 to 1999. The data at Glencourse was checked for consistency with neighboring gauge stations. On average the annual streamflow at Metiyadola, Algoa Bridge and Kitulagala (Fig. 2) accounts for approximately 40%, 20%, and 26% of the annual streamflow at Glencourse (4500 MCM).

We have compared the streamflow at Glencourse based on upstream and downstream stations, and found the
Stream flow
Normal
Catchment rainfall

Glencourse
the reservoirs affect only 10% of
may be reasonably overlooked for this analysis given that
of reservoir management on streamflow at Glencourse
and a drainage area of 236 square kilometers. The impacts
small storage capacity of 169 million cubic meters (MCM)
electricity generation stations. These reservoirs have a
shorter record of the inflow to the
Moussakelle
ment. The findings reported here were verified with a
reaches of the
Kelani
starting in 1953 as storage for hydro-
energy generation stations. These reservoirs have a
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of reservoir management on streamflow at Glencourse
may be reasonably overlooked for this analysis given that
the reservoirs affect only 10% of the Glencourse
catchment. The findings reported here were verified with a
shorter record of the inflow to the Moussakelle reservoir
(Fig. 2).

Global circulation

Global circulation fields at 200 hPa pressure level were ob-
tained from the NCEP–NCAR reanalysis at monthly fre-
quency starting from 1948 (Kistler et al., 2001).

Methods

Correlation analysis

The Pearson product moment coefficient of linear correla-
tion was applied to identify the streamflow or rainfall rela-
tionships with ENSO indices (Wilks, 1995). The technique of
partial correlations was used to find the relative significance
of additional variables by removing the correlation of ENSO
index with it in a statistical sense. The partial correlation
(Fisher, 1925) between Y and X controlling for W may be
obtained as

\[ r_{XY}^W = \frac{r_{XY} - r_{XW}r_{YW}}{\sqrt{(1 - r_{XW}^2)(1 - r_{YW}^2)}} \]

Contingency tables

Contingency tables are constructed to identify the influence
of ENSO on a variable such as streamflow based on historical
data (Wilks, 1995). The ENSO phases are identified based on
the prevalent value for an ENSO index in categories as El
Niño, Neutral and La Niña. Similarly, the streamflow are
segregated in terciles representing “below-normal”,
“near-normal” and “above-normal” flow. The occurrences
of ENSO phases and streamflow conditions in different
ENSO/streamflow tercile combinations are tabulated pro-
viding a summary of the association between ENSO phases
and streamflow terciles.

Heidke skill scores

The Heidke skill score (HSS) is a measure of forecast skill
that is widely used when the forecasts and corresponding
observations are expressed in categories as below normal,
near-normal and above-normal (Wilks, 1995). The score is
based on the number of forecasts where the category with
the largest forecasted probability turned out to be correct.
The skill is given by HSS = 100 (C – E)/(N – E), where C
is the number of correct forecasts, E is the number of cor-
correct forecasts expected by chance and N is the total num-
ber of forecasts. In the computation of the Heidke score, we
used the observed occurrences of rainfall and ENSO episodes
to determine the probabilities expected by chance. An
all-correct forecast results in a score of 100, while a fore-
cast with as many correct as expected by chance scores 0.
The typical skill of seasonal predictions which is obtained
operationally based on Global Climate Models over land
is of the order of 10 (Mason et al., 1999). While the Heidke
skill score has its drawbacks, it serves as a quick but
approximate index of predictability.

Results

Mean annual cycle

The rainfall climatology of Sri Lanka has a bimodal distri-
bution (Fig. 3a) with peaks around May and November due to
the rain associated with the passage of the Inter-Tropical
convergence zone over Sri Lanka (Bamford, 1922). In addi-
tion, winter monsoonal influences and cyclonic storms from
the Bay of Bengal contribute to high rainfall from October to December (Zubair and Ropelewski, 2006). The Western hill slopes receive considerable orographic rainfall from May to September when strong Westerly winds prevail. The Kelani catchment is located on one of the steepest westward facing hill slopes.

As there is year round rainfall and streamflow in this catchment, there is no clear-cut means of demarcating the seasons. Most useful for water resources management is the traditional demarcation of seasons based on the agricultural seasons (Maha from October to March and Yala from April to September). Decisions regarding seasonal water allocations are made at the start of the seasons.

Relationships with large scale circulation

During El Niño episodes, the anomalous warming in the tropical Western Pacific Ocean leads anomalous convection over the Eastern tropical Pacific Ocean warm pool setting up an anomalous zonal large scale circulation referred to as the Walker circulation. The 200 hPa velocity potential anomaly fields is a good proxy for representing the Walker circulation (Kumar et al., 1999). Global circulation fields are available from 1948 onwards from the NCEP–NCAR analysis. We constructed the composite of the April–September 200 hPa velocity potential anomaly fields for the El Niño episodes from 1948 to 2000 (Fig. 4a). The velocity potential anomaly field during warm episodes shows that there is enhanced subsidence over South and South-East Asia and parts of the Indian Ocean. Subsidence over the Indian Ocean including Sri Lanka leads to reduction in cloud formation and rainfall consistent with the observed reduction in rainfall during the Yala.

We also constructed the simultaneous correlation between the April–September streamflow and the Indo-Pacific SST (Fig. 4b): it shows a high correlation with the eastern equatorial Pacific Ocean and the Central Indian Ocean with a spatial pattern reminiscent of ENSO providing further evidence for linkage between ENSO and the streamflow during Yala.

During the October–December period, the zone of subsidence over the Indian Ocean and East Africa is shifted north-eastwards and as a result convection over Sri Lanka and Southern India is enhanced during El Niño episodes (Zubair and Ropelewski, 2006).

ENSO–streamflow relationships

Yala (April–September)
The Kelani streamflow during Yala declines during warm ENSO episodes and is enhanced during cold ENSO episode on average (Fig. 5a). The average streamflow during Yala in the La Niña phase is 32% higher than that in the El Niño phase (Fig. 3b). The seasonal streamflow during Yala has a negative correlation with NINO indices that is significant at the 95% confidence limit (Table 1). The above relationships hold, albeit with lower levels of statistical significance, for the streamflow at the headstream above the Maussakelle reservoir inflow as well.

![Figure 4](image1.png)

**Figure 4** (a) Composites of the April–September velocity potential anomalies ($\times 10^{-6}$ m$^2$ s$^{-1}$) at 200 hPa for El Niño seasons are shown. The El Niño seasons were 1963, 1965, 1968, 1969, 1972, 1976, 1977, 1982, 1986, 1987, 1991, 1994, 1997 and 2002. (b) The correlation of April–September sea surface temperatures with simultaneous Glencourse streamflow for 1975–2000. Correlations that are significant at 99%, 95% and 90% correspond to $r = 0.44$, 0.38 and 0.32 ($n = 26$).

![Figure 5](image2.png)

**Figure 5** The time series of aggregate streamflow and aggregate catchment rainfall for Glencourse and the concurrent average NINO3.4 index are shown for (a) Yala, (b) Early Maha and (c) Late Maha.
A relationship associating El Niño with Above-Normal, Neutral with near-normal and La Niña with below-normal streamflow is verified in 24 occasions out of 51 Yala seasons (Table 3a) resulting in a Heidke Skill score of 21.

**Maha (October—March)**

The influence of ENSO on the Maha rainfall changes after the first half of this season. During the El Niño phase there is enhanced convection over Sri Lanka from October to December (Zubair and Ropelewski, 2006) but in the months that follow there is enhanced subsidence (Zubair and Chandimala, 2006). Therefore, to obtain the most predictability based on ENSO, we need to consider the October—December and January—March periods separately.

**Early Maha (October—December)**

The streamflow during this season (Fig. 5b) show modest drops in the second half of the record. The October—December rainfall increases during the El Niño and declines during La Niña. This relationship is clearer cut for rainfall than streamflow. During the first half of the Maha season, the streamflow during the El Niño phase is 11% greater than that during the La Niña phase. Simultaneous correlation of October—December (Early Maha) streamflow with ENSO indices are at insignificant levels (Table 1) with weak signs of an El Niño–Wet and La Niña-Dry association (Table 3b), the Heidke skill score is only 9.

**Late Maha (January—March)**

The January—March streamflow (Fig. 5c) declines on average during both ENSO phases (Fig. 3b). The streamflow during both El Niño and La Niña phases are less (−25% and −13%, respectively) than that during the Neutral phase.

The contingency table based on NINO3.4 (Table 3c) shows that streamflow values tend to an El Niño-Dry and La Niña-Wet relationship with NINO3.4 resulting in a Heidke skill score of 12. The January—March (Late Maha) streamflow has a significant relationship with NINO12 in the far Eastern Pacific Ocean \( r = −0.41 \).

**ENSO—rainfall relationships**

**Yala (April—September)**

The Yala rainfall during the La Niña phase is 13% higher than that during the El Niño on average (Fig. 3b). The ENSO—rainfall correlation during the Yala season (Table 2) is markedly less than that for the ENSO—streamflow correlation (Table 1).

Predictions of rainfall associating El Niño with Above-Normal, Neutral with near-normal and La Niña with below-normal results is verified in 23 occasions out of 51 Yala seasons (Table 3a) resulting in a Heidke Skill score of 18. Overall, the analysis shows that ENSO based predictions of Yala rainfall has some skill which is less than that obtained for streamflow predictions.
Maha (October–March)
We consider the first and second half of the season separately.

Early Maha (October–December)
During the first half of the Maha season, the rainfall during
the El Niño phase is 23% greater than that during the La Niña
phase (Fig. 3b). The correlation of ENSO indices with Octo-
ber–December rainfall is more significant (Table 2) than
with streamflow (Table 1). The contingency table (Table
3b) shows significant distinction between the El Niño and
La Niña phases for the October–December season which is
brought out by a Heidke skill score of 18.

Late Maha (January–March)
During the second half of the season, the rainfall during
both El Niño and La Niña phases are modestly less (–22%
and –5%, respectively) than that during the Neutral phase.

Rainfall and ENSO indices are negatively correlated yet,
only the NINO12 index is statistically significant at the 95%
level. The Heidke skill score for an ENSO based prediction
assuming lower rainfall values for El Niño and La Niña is
15 (Table 3c).

Rainfall and streamflow relationships with Indian
Ocean indices
Regional influences particularly from the Indian Ocean are
likely to have a significant influence on the Kelani river basin.
Recently, the "Equatorial Indian Ocean Oscillation" (EQUI-
NOO) (Gadgil et al., 2004) has been found to be useful along
with ENSO in explaining the inter-annual variations in the In-
dian summer monsoon rainfall (May–September). Maity and
Nagesh Kumar (2006) presented a Bayesian dynamic model
for predicting monthly streamflow during the summer in
India.

Gadgil et al. (2004) have suggested the use of the Equa-
torial Zonal Wind (EQWIN) as an index of the EQUINOO phe-
nomenon. The streamflow and rainfall in the Kelani
catchment show only a modest correlation with the EQWIN
(Table 4). Further analysis using the sum of the indices (EQ-
WIN + NINO3.4) following Gadgil et al. (2004) did not yield

Table 3
Contingency table for the ENSO association with simultaneous streamflow and catchment rainfall (in brackets) at
Glencourse between 1950 and 2000 for (a) Yala, (b) early Maha and (c) late Maha

<table>
<thead>
<tr>
<th></th>
<th>Below-normal</th>
<th>Near-normal</th>
<th>Above-normal</th>
</tr>
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<tbody>
<tr>
<td>(a) Yala (April–September)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall (streamflow)</td>
<td>&lt;1795 mm (&lt;2529 mm)</td>
<td>1795–2212 mm (2529–2814 mm)</td>
<td>&gt;2212 mm (&gt;2814 mm)</td>
</tr>
<tr>
<td>El Niño (&gt;0.4 °C)</td>
<td>6 (6)</td>
<td>6 (6)</td>
<td>3 (3)</td>
</tr>
<tr>
<td>Neutral</td>
<td>7 (7)</td>
<td>11 (11)</td>
<td>7 (7)</td>
</tr>
<tr>
<td>La Niña (&lt;–0.4 °C)</td>
<td>3 (3)</td>
<td>2 (1)</td>
<td>6 (7)</td>
</tr>
<tr>
<td>(b) Early Maha (October–December)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall (streamflow)</td>
<td>&lt;820 mm (&lt;1032 mm)</td>
<td>820–1015 mm (1032–1247 mm)</td>
<td>&gt;1015 mm (&gt;1247 mm)</td>
</tr>
<tr>
<td>El Niño (&gt;0.4 °C)</td>
<td>1 (2)</td>
<td>7 (5)</td>
<td>6 (7)</td>
</tr>
<tr>
<td>Neutral</td>
<td>4 (3)</td>
<td>3 (6)</td>
<td>5 (4)</td>
</tr>
<tr>
<td>La Niña (&lt;–0.4 °C)</td>
<td>11 (11)</td>
<td>8 (8)</td>
<td>6 (6)</td>
</tr>
<tr>
<td>(c) Late Maha (January–March)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall (streamflow)</td>
<td>&lt;217 mm (&lt;187 mm)</td>
<td>217–304 mm (187–427 mm)</td>
<td>&gt;304 mm (&gt;427 mm)</td>
</tr>
<tr>
<td>El Niño (&gt;0.4 °C)</td>
<td>6 (6)</td>
<td>2 (5)</td>
<td>2 (3)</td>
</tr>
<tr>
<td>Neutral</td>
<td>6 (3)</td>
<td>7 (6)</td>
<td>8 (4)</td>
</tr>
<tr>
<td>La Niña (&lt;–0.4 °C)</td>
<td>4 (7)</td>
<td>9 (8)</td>
<td>7 (10)</td>
</tr>
</tbody>
</table>

The ENSO phases are defined based on the seasonal average NINO34 values as follows: El Niño (NINO34 >0.4), Neutral
(–0.4 > NINO34 > 0.4) and La Niña (<–0.4 > NINO34). The rainfall categories are based on terciles and the limits of these terciles are
indicated for rainfall with values in brackets for streamflow.

Table 4
The correlation of the Yala (April–September) rainfall (RF) and streamflow (SF) with the NINO34, NDMI, EQWIN,
EQWIN + NINO34 and CEIO

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>NINO34</td>
<td>–0.30</td>
<td>–0.33</td>
<td>–0.02</td>
</tr>
<tr>
<td>NDMI</td>
<td>0.14</td>
<td>0.13</td>
<td>0.27</td>
</tr>
<tr>
<td>EQWIN</td>
<td>–0.07</td>
<td>0.03</td>
<td>–0.12</td>
</tr>
<tr>
<td>EQWIN + NINO34</td>
<td>–0.24</td>
<td>–0.19</td>
<td>–0.11</td>
</tr>
<tr>
<td>CEIO</td>
<td>–0.40</td>
<td>–0.35</td>
<td>–0.41</td>
</tr>
</tbody>
</table>

Correlations that are significant at 99%, 95% and 90% corresponding to $r = 0.35$, 0.27 and 0.23 ($n = 53$) and to $r = 0.45$, 0.35 and 0.29
($n = 30$) are shown in bold, bold italics and italics.
enhanced correlation compared to that using NINO3.4 alone (Table 4).

The Indian Ocean Dipole (IOD) has a strong relationship with the September–December rainfall in Sri Lanka (Zubair et al., 2003). However, the relationship of the IOD index of Normalized Dipole Mode index (NDMI) with the Kelani rainfall and streamflow was insignificant during the Yala (Table 4).

The Yala rainfall correlates with the central equatorial Indian Ocean (CEIO) SST anomaly (Fig. 4b) at significant levels for 1975–2000 \( r > 0.38 \). The CEIO index is defined as the mean SST anomaly in the region bounded by 60°E to 90°E and 10°S to 10°N. Streamflow and rainfall during Yala had simultaneous correlations \( r = -0.35 \) and \(-0.40 \), respectively) with CEIO that were significant at the 95% level (Table 4). There is a relationship between ENSO and the Indian Ocean SST brought about by the Walker circulation. However, there are also independent modes of variability in the Indian Ocean. The partial correlation of the streamflow with simultaneous CEIO during Yala controlling for NINO3.4 was \(-0.24 \) and the partial correlation of NINO3.4 controlling for CEIO was \(-0.26 \). Both of these are significant at the 90% level. Hence, it shall be useful to consider both the Pacific and Indian Ocean in developing a forecast scheme.

**Model prediction**

There are a variety of streamflow prediction schemes based on multiple predictors that have been previously reported on. Here, we are only presenting a proof of concept as to the viability of the ENSO based prediction scheme. We have used a principal component regression scheme (Ward and Folland, 1991) that uses the March SST in the Indo-Pacific region (30°S–30°N and 30°E–60°W) to predict the Kelani River seasonal streamflow at Glencourse during Yala from 1960 to 1997. The predictors are chosen as the principal components of the SST’s. The use of the leading mode (Fig. 6a) alone which accounts for 30% of the variance in the SST was found to give as good a prediction as using the first five principal components. The first principal component essentially contains the signature of ENSO in the Indo-Pacific region with warming in the Eastern equatorial Pacific and Central equatorial Indian Ocean. We used the period after 1960 for the cross-validated predictions as there has been a dramatic change in the streamflow and rainfall relationships with SST prior to 1950s (Zubair and Chandimala, 2006). The predictions for streamflow are shown in Fig. 6b. The Pearson correlation between the observed streamflow during Yala and the cross-validated prediction is 0.5 and the Heidke skill is 31. The predictions for the rainfall (not shown) have slightly lower skill with a Pearson correlation of 0.44 and a Heidke skill score of 35.

The predictions of streamflow during Yala generally have the right anomaly except for seasons such as during 1976, 1980, 1986, 1991, 1993, 1995 and 1998. The principal discrepancy arises from the transition that often takes place in ENSO after the boreal spring — thus SST anomalies observed in March may differ considerably from the SST anomalies in the succeeding months. As the Yala season unfolds, it will be useful to monitor the SST conditions so that modifications to the seasonal predictions may be issued for the remainder of the season.

The prediction scheme for the early and late halves of the Maha rainfall are not presented here but based on the correlation values and skill scores, these are likely to yield predictions which are as skillful as for Yala. The correlation values for October–December rainfall with NINO3.4 \( r = -0.44 \) is significant at the 99% level and the Heidke skill score is 18. While the correlation value for the January–March rainfall with NINO3.4 is not significant \( r = -0.10 \), this is due to a non-linear relationship with ENSO where rainfall in both El Nino and La Nina phases decline in relation to where there are neutral conditions. The predictability is captured by the Heidke skill score of 15.

**Discussion**

The differences in saliency of ENSO relationships with streamflow and rainfall during the different seasons were brought out in this study. The correlation of ENSO indices with streamflow during Yala is greater than that with rainfall. On the other hand, the correlation between ENSO indices and rainfall during the October–December period is greater than that with streamflow. The latter disparity is due to opposing ENSO influences on rainfall in the months before and after October. Thus during a typical El Niño episode, dry anomalies from April to September are followed by wet anomalies from October to December and dry anomalies from January to March in the next year. During the typical El Niño episode, the anomalously dry April–September period leads up to an anomalously wet October–December period. Consequently, the wet rainfall anomalies during October–December are not immediately reflected in the streamflow anomalies from October to December as some of the rainfall excess is used to replenish the anomalously dry soil moisture. ENSO based rainfall predictions can be

![Figure 6](image-url)

**Figure 6** (a) The leading principal component of the Indo-Pacific SST mode during Yala from 1960 to 2000. (b) The prediction of Glencourse streamflow in cross-validated mode based on the leading principal component and the observed Yala streamflow.
used along with a hydrological model or rainfall—runoff relationships to predict the October—December streamflow.

We have established relationships between SST and streamflow and rainfall that are simultaneous. To be able to predict the streamflow, lag—lead relationships are required. An alternative means of taking advantage of any simultaneous relationship is to use seasonal predictions of ENSO and SST along with the established relationships. Predictions for SST based ENSO indices are made by several forecasting centres (see http://iri.columbia.edu/climate/ENSO/). In either case, there could be a deterioration of skill. But as shown in the case of the streamflow predictions during Yala, it is likely that useful relationships can be found even after accounting for the lag—lead relationships.

The results shown here for Yala are similar to those reported for Indian rainfall during the summer monsoon period. The lack of saliency of the equatorial Indian Oscillation in explaining the rainfall in Sri Lanka is interesting and worthy of further investigation. There are significant differences in the circulation in the boreal summer between India and Sri Lanka during this period. For example, the Tropical Convergence Zone is located over the Indian subcontinent during this period.

The predictability of both streamflow and rainfall for the Yala season progresses.

We have presented here a proof of concept that predictions based on SST shall be useful. Further investigations of influences of other climatic precursors such as volcanic eruptions and Eurasian snow cover on streamflow and rainfall may improve the prediction scheme. Finally, given the imperfect information that is used in the prediction scheme, the imperfect understanding of the climate system and intrinsic chaotic nature of the climate system all predictions can only legitimately represented as probabilistic. This probabilistic nature should be explicitly represented to users.

Conclusions

This work has shown that there is a statistically significant influence of ENSO on Kelani streamflow and rainfall. This influence is contrasting in different seasons and shows subtle differences between rainfall and streamflow. Useful relationships were brought out by stratifying the analysis by the appropriate season. The streamflow during Yala had a consistent ENSO influence with warm phases leading to reduced flow on average. ENSO indices had correlations with streamflow during Yala ($r = -0.41$ with NINO3.4) and the rainfall during early Maha ($r = 0.44$ with NINO3.4) that were significant at the 99% level. The contingency tables of ENSO state versus flow anomalies provided further support for the predictability of streamflow during Yala. The streamflow during Yala also had a correlation ($r = -0.35$) with the Central Equatorial Indian Ocean SST that was significant at the 95% level.

We used regression between the principal components of the March SST in the Indo-Pacific region to predict streamflow during Yala. The first principal mode which explains 30% of the SST variance was able to predict the streamflow with a correlation of 0.5 after 1960 in a cross-validated mode. The prediction scheme was prone to error in seasons in which the ENSO conditions reversed in spring such as during 1998 and thus this prediction scheme should be updated as the Yala season progresses.

The prediction of streamflow during Maha is best carried out separately for the two halves of the season. During the early Maha (October—December), rainfall had a correlation with NINO3.4 that was significant at the 95% level. During the late Maha (January—March), streamflow and rainfall shows a 25% and a 22% drop during the El Niño phase compared to the Neutral phase. During this season, both streamflow and rainfall are diminished during the La Niña phase as well. Thus during an El Niño episode, the rainfall increases in the first half of the season and declines in the second half on average. During La Niña episodes, the rainfall declines on average throughout the season.

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