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Streamflow prediction using multi-site rainfall obtained from hydroclimatic teleconnection

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SUMMARY

Simultaneous variations in weather and climate over widely separated regions are commonly known as "hydroclimatic teleconnections". Rainfall and runoff patterns, over continents, are found to be significantly teleconnected, with large-scale circulation patterns, through such hydroclimatic teleconnections. Though such teleconnections exist in nature, it is very difficult to model them, due to their inherent complexity.

Statistical techniques and Artificial Intelligence (AI) tools gain popularity in modeling hydroclimatic teleconnection, based on their ability, in capturing the complicated relationship between the predictors (e.g. sea surface temperatures) and predictand (e.g., rainfall). Genetic Programming is such an AI tool, which is capable of capturing nonlinear relationship, between predictor and predictand, due to its flexible functional structure. In the present study, gridded multi-site weekly rainfall is predicted from El Niño Southern Oscillation (ENSO) indices, Equatorial Indian Ocean Oscillation (EQUINOO) indices, Outgoing Longwave Radiation (OLR) and lag rainfall at grid points, over the catchment, using Genetic Programming.

The predicted rainfall is further used in a Genetic Programming model to predict streamflows. The model is applied for weekly forecasting of streamflow in Mahanadi River, India, and satisfactory performance is observed.

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1. Introduction

Basin-scale streamflow prediction is an important step in water resources management for sustainable development. The variation of basin-scale streamflow is influenced by rainfall depth, its distribution pattern, catchment characteristics and the ground water contribution to the streamflow. The rainfall distribution, over the catchment, depends on local meteorology, large scale atmospheric circulation patterns and the geography of the catchment. It may be difficult to predict weekly streamflow accurately, by just considering the rainfall of few previous weeks, because the rainfall in current week also has substantial contribution to streamflow. This is especially true for monsoon season, when the soil is saturated, leading to insignificant infiltration. In the present study, a two-step approach is proposed for weekly streamflow prediction. In first step, current (weekly) multi-gridded rainfall is predicted with Genetic Programming (GP), based on large scale atmospheric circulation patterns, OLR and lag rainfall at grid points. Current step weekly streamflow is then predicted, by using observed gridded rainfall, up to previous weekly time step and GP predicted multi-gridded rainfall, at current weekly time step.

A single step model, for streamflow forecasting, is also developed, by using same inputs and the results are compared with the performance of two step model.

The objectives of this study are summarized as following:

(1) To develop GP-based models, for weekly multi-site (multi-gridded) rainfall prediction, based on large scale atmospheric circulation patterns with hydroclimatic teleconnection, lag multi-gridded rainfall and OLR.
(2) To develop GP-based weekly basin-scale streamflow prediction model, based on observed gridded rainfall at few previous weekly time steps, GP predicted gridded rainfall at current time step and lagged streamflow at immediate previous weekly time step.
(3) To assess the improvement in streamflow predictions due to inclusion of current step (week), GP predicted rainfall in the input set, in addition to the observed gridded rainfall up to the lag-1 weekly time step.
(4) To compare the results of the aforesaid two-step model with a single-step model, that uses lag streamflow, ENSO indices, EQUINOO indices, OLR anomaly, historical avg. rainfall and rainfall at the all grid points over last six weeks.

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The methodology adopted for streamflow prediction in the two-step model can be visualized in flowchart (Fig. 1a). The first step deals with the multi-gridded rainfall prediction, and the second step deals with the basin-scale streamflow prediction.

Similarly the methodology of a single-step model can be seen in flowchart (Fig. 1b).

The rainfall as well as streamflow-prediction models are developed by using Genetic Programming tool. The methodology is different from the methodologies mentioned in the literature (Eltahir, 1996; Piechota et al., 1997; Chiew et al., 1998; Chandimala and Zubair, 2007).

The novelty of this method lies in the inclusion of predicted current week rainfall in streamflow-prediction model that contributes to current-week streamflow, especially in monsoon season.

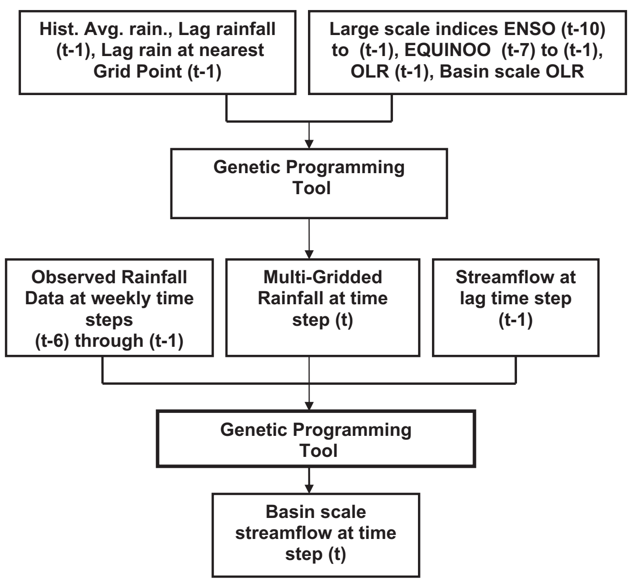

Fig. 1a. Flowchart of multi-gridded rainfall prediction followed by basin-scale streamflow prediction using Genetic Programming.

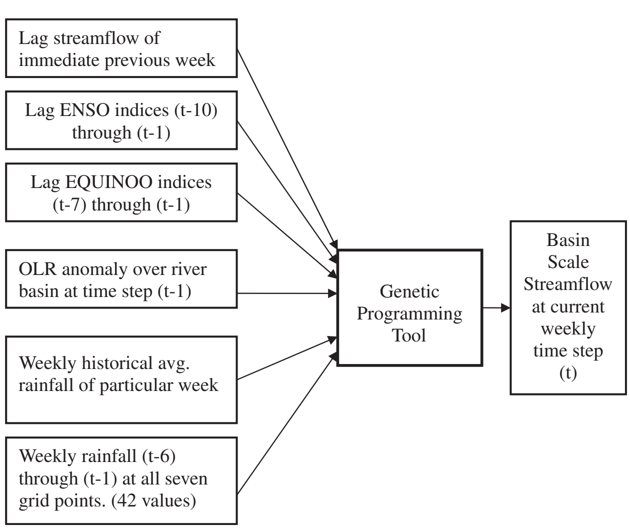

Fig. 1b. Flowchart of basin-scale streamflow prediction by single step method using Genetic Programming.

2. Influence of large scale atmospheric circulation patterns over spatio-temporal rainfall distribution

Simultaneous variations in weather and climate over widely separated regions on earth have long been noted in the meteorological literature. Such recurrent patterns are commonly referred as "teleconnections". Rainfall distribution patterns over the continents are significantly linked with the atmospheric circulation through hydroclimatic teleconnection.

It is also established that the natural variation of rainfall is linked with these large scale atmospheric circulation patterns, through hydroclimatic teleconnection (Dracup and Kahya, 1994; Eltahir, 1996; Jain and Lall, 2001; Douglas et al., 2001; Ashok et al., 2004; Marcella and Eltahir, 2008; Maity and Nagesh Kumar, 2006, 2008). Hydroclimatic teleconnection between Indian Summer Monsoon Rainfall and large scale atmospheric circulation patterns over Pacific Ocean and Indian Ocean was established in literature (Rasmusson and Carpenter, 1983; Parthasarathy et al., 1988; Krishna Kumar et al., 1999; Ashok et al., 2001; Li et al., 2001; Gadgil et al., 2003, 2004; Maity and Nagesh Kumar, 2006).

El Niño Southern Oscillation (ENSO) is the coupled ocean–atmosphere mode of variability in the tropical Pacific Ocean (Cane, 1992), whereas Indian Ocean Dipole (IOD) mode is the same over tropical Indian Ocean (Saji et al., 1999). El Niño Southern Oscillation (ENSO) is related to ocean–atmosphere interaction in the equatorial Pacific Ocean. El Niño represents anomalous warming of tropical Pacific Ocean, while La Niña represents the anomalous cooling of the oceans in the same area. This oscillation observed over the Pacific Ocean gives rise to periodic shifts in interacting winds and sea-surface exchanges. Both El Niño and La Niña are accompanied by changes in atmospheric pressures between eastern and western Pacific Ocean, known collectively as ENSO.

Another phenomenon called as Indian Ocean Dipole mode (IOD) has been observed in Indian Ocean (Saji et al., 1999), which also influences the Indian Summer Monsoon Rainfall. IOD can be described as a pattern of internal variability with anomalously low sea surface temperatures off Sumatra and high sea surface temperatures in the western Indian Ocean, with accompanying wind and precipitation anomalies (Saji et al., 1999). IOD mode has important applications on climate variability in the regions surrounding the Indian Ocean, like east Africa and Indonesia. Ashok et al. (2001) have shown that the IOD plays an important role as a modulator of the ENSO–ISMR relationship. Equatorial Indian Ocean Oscillation (EQUINOO) is the atmospheric component of the IOD mode. Equatorial zonal wind index (EQWIN) is considered as an index of EQUINOO, which is defined as negative of the anomaly of the zonal component of surface wind in the equatorial Indian Ocean Region (60°E–90°E, 2.5°S–2.5°N) (Gadgil et al., 2003, 2004). Gadgil et al. (2003, 2004) established that Indian Summer Monsoon Rainfall is not only associated with ENSO but also associated with EQUINOO.

It is observed that the strength of the hydroclimatic teleconnection decreases for smaller spatio-temporal scale. However, still, significant influence exists for sub-divisional scale for most of the geographical locations. The nature of the relationship varies across different subdivisions and different seasons (Kane, 1998; Maity and Nagesh Kumar, 2007).

Effect of El Niño Southern Oscillation (ENSO) on streamflow has been widely discussed in hydro-climatic literature. Dracup and Kahya (1994) developed a relationship between streamflow in United States of America and La Niña events. Eltahir (1996) assessed the impacts of El Niño on the flow of the Nile River in Egypt. Piechota et al. (1997) pointed out, that, relationship exists between western US streamflow and atmospheric circulation patterns, during ENSO. Chiew et al. (1998) discussed effects of ENSO on Australian rainfall, streamflow and drought. Effects of ENSO and Pacific

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