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Increasing streamflow forecast lead time for snowmelt-driven catchment based on large-scale climate patterns

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ABSTRACT

This study focuses on improving the spring–summer streamflow forecast lead time using large scale climate patterns. An artificial intelligence type data-driven model, Support Vector Machine (SVM), was developed incorporating oceanic–atmospheric oscillations to increase the forecast lead time. The application of SVM model is tested on three unimpaired gages in the North Platte River Basin. Seasonal averages of oceanic–atmospheric indices for the period of 1940–2007 are used to generate spring–summer streamflow volumes with 3-, 6- and 9-month lead times. The results reveal a strong association between coupled indices compared to their individual effects. The best streamflow estimates are obtained at 6-month compared to 3-month and 9-month lead times. The proposed modeling technique is expected to provide useful information to water managers and help in better managing the water resources and the operation of water systems.

1. Introduction

Streamflow is an important hydrologic variable that impacts water supply [19], flood protection [62,26,8,10,82], and drought mitigation strategies [74,87]. In the rivers of the western United States, snowmelt is the primary source, contributing about 50–80% of the total streamflow [88,89]. Streamflow in these rivers is highly seasonal in nature, and majority of streamflow occurs due to snowmelt during late spring–summer (April–July). The timing and quantity of streamflow is critical for the regional water supply because it supplies water at such times when agricultural, domestic, industrial and recreational water demands are at their peak.

The western United States experiences high variability in precipitation, having wet and dry cycles, and temperature, with warm and cold phases; this leads to year-to-year differences in the timing and quantity of snowmelt and streamflow [42,66,40]. Water management is becoming more challenging due to growing water demand caused by increase in population and water quality issues in the region [75,81,80,100,101]. Variability in streamflow is a challenge for water managers who need to formulate strategies to store surplus water in wet years in order to have enough carry-over reservoir storage to meet water demands during drought years [99,5–7].

Several research efforts have documented the correlation of oceanic climatic phenomena, such as the El Niño-Southern Oscillation (ENSO) [20,30,43,78,28,92], the Pacific Decadal Oscillation (PDO) [52,30,55], the Atlantic Multidecadal Oscillation (AMO) [56,54], and the North Atlantic Oscillation (NAO) [93,38] with the variability in streamflow worldwide, including the western United States [1,30,32,55,28,93,38,41]. Tootle et al. [93] found that ENSO strongly influences streamflow variability over the western United States; a weaker influence due to other atmospheric–oceanic circulations, such as PDO, NAO and AMO, also was reported. The influence of PDO and AMO on droughts over the western United has been reported by McCabe et al. [56]. Similarly, Ellis et al. [23] analyzed patterns of drought in the Colorado River Basin and their teleconnection with the ENSO, PDO, and AMO. Several studies also have reported a strong influence of such oceanic–atmospheric anomalies as ENSO, AMO, and PDO on the persistent wet and dry cycles observed over the Continental United States [34,58,53,105].

In regions where snowfall comprises of a significant portion of precipitation, the variability in seasonal snow cover often has been associated with atmospheric–oceanic circulations. Clark et al. [18] documented the influence of NAO and regional oceanic cycles, known as the Eurasian Type 1 (EU1) pattern and the Siberian pattern (SIB), respectively, on Eurasian snow extent. For the western United States snowfall, Hunter et al. [35] reported a strong relationship of ENSO and relatively weak correlations of PDO, AMO and NAO anomalies. Neal et al. [67] studied the rivers fed by glaciers in Alaska and reported that snowmelt responds differently to the PDO induced regime shift during 1976–1977. Another study

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on glacial rivers in Alberta by Lafrenière and Sharp [48] reported different effects of the 1997–1998 El-Niño event compared to an adjacent snowmelt-fed basin. Moore and Demuth [60] related streamflow variability of the Place Glacier with PDO; they found a negative correlation with the winter time variability and a positive correlation with the summer time variability. Clark et al. [17] found significant effects of ENSO on seasonal snowpack evolution in the Columbia and Colorado River Basins. Several other research studies have reported similar variability in snow cover due to ENSO, PDO, and NAO over the western United States, Canada, and other regions of the world [17,55,64]. The possibility of snowmelt-driven streamflow responding to several modes of climate variability, thus presents clear implications for water resources management and forecasting.

It is evident that atmospheric–oceanic phenomena introduce a high degree of variability in hydro-climate globally, particularly in the western United States. However, their correlations with hydro-climate variables also provide an opportunity to predict streamflow in advance. Due to the complex interaction between streamflow and oceanic oscillation and relatively incomplete understanding, empirical [2,3] or physically based model cannot be constructed to study these relationships [51]. One alternative is using Artificial Intelligence (AI) type models, also referred to as machine-learning or data-driven models. In terms of AI-type models, Artificial Neural Network (ANN) models often are the prime choice of many researchers for modeling various hydrological processes. ANN models have been utilized by numerous researchers in predicting streamflow [33,107,91,15,9,45]. The American Society of Civil Engineers Task Committee report [11,12] provides a detailed discussion on the theoretical concepts and hydrologic applications of ANN.

Although, ANN's have been applied extensively in different fields, there are some drawbacks associated with the use of different ANN algorithms. First being the possibility of getting trapped in local minima. Next, subjectivity is involved in the choice of ANN model architecture and structure [90]. Additionally, the architecture and weights in several ANN algorithms are determined by iterative trial and error process, which becomes time consuming [51]. Due to these drawbacks, there is a need for a more sophisticated AI-type data driven model that is capable of efficiently representing the multifaceted interaction between oceanic–atmospheric oscillations and streamflow.

With this motivation, the current research incorporates large-scale climate information in a data-driven model to increase the streamflow forecast lead time for the North Platte River Basin (NPRB), located in Wyoming. A simple, robust, and parsimonious model called the Support Vector Machine (SVM) is applied to capture the variability introduced in streamflow by oceanic oscillations. Globally, several modes of climate patterns have been developed that have been related to the magnitude and variability of streamflow at regular cycles. The climate variability of the United States, particularly the western U.S., has been extensively studied in relationship with PDO, NAO, AMO, and ENSO indices. These inter-annual, decadal, and multi-decadal indices reflect variations in climate and help to explain the variance of extreme events, such as floods and droughts [104]. Moreover, these are the only four oceanic indices for which reconstructed data have been developed. Therefore, this current research used the most commonly studied and best understood oceanic–atmospheric oscillations in the western U.S. – PDO, NAO, AMO, and ENSO – ranging from 1940–2007 (68 years) for increasing the lead time of streamflow forecasts to three to nine months for spring–summer (April–July) at three unimpaired stations in the NPRB.

A modified predictive SVM framework is proposed to capture the variability exhibited by streamflow in relation to oceanic–atmospheric oscillations. Past efforts by Soukup et al. [86] provided a categorical lead time of 3–6 months for streamflow forecasts for NPRB, utilizing a nonparametric approach that incorporated climate information. This approach, based on linear discriminant analysis (LDA), is attractive and useful in providing categorical streamflow estimates. However, the Probability Distribution Function for each forecast category is estimated using kernel density methods and also the weights are identified using an optimization method [77]. Moreover, the model fits the data, assuming that the historic data represents the entire population [86]. Additionally, these methods are more useful for providing a qualitative understanding of relationships between climate patterns and hydrologic variability. For operational purposes, water managers are more interested in quantifying the magnitude of the hydrologic response. Therefore, the proposed SVM approach in the current study is expected to offer potential improvements over LDA as (1) it fits the function using the entire data set and (2) climate induced streamflow volumes are generated opposed to exceedance probabilities in LDA approach.

In this study, SVM streamflow estimates were compared with a feed-forward, back-propagation ANN model as well as a Multivariate Linear Regression (MLR) model. This ANN-type model has been extensively used by researchers in modeling different hydroclimatic variables [76,46,91,33,9,57]. The other type of model developed was the parametric Multivariate Linear Regression (MLR) model, which consists of oceanic-oscillations as the predictors and spring–summer streamflow as the predictand. The datasets used to develop the corresponding ANN model and MLR model were the same as in the SVM model. All three models were evaluated using root mean square error (RMSE)-observations standard deviation ratio (RSR), correlation coefficient (R), Nash Sutcliffe coefficient of efficiency (NSE), and linear error in probability space (LEPS) skill score (SK).

This paper is organized as follows. The study area and data used in the current research are described in Section 2. The SVM modeling framework is described in Section 3. Sections 4 and 5 presents the results and discussion of results. Lastly, Section 6 concludes the paper.

2. Study area and data

2.1. Study area

The North Platte River (Fig. 1) is a branch of the Platte River flowing through Colorado, Wyoming, and Nebraska, roughly 1100 km long. It unites with the South Platte River in western Nebraska to form the Platte River. The river's flow is controlled by a series of dams strategically located along its course; it provides municipal water supplies, irrigation, hydroelectric power, and recreational opportunities. The North Platte River is fundamental to the local ecosystem; its banks provide a wildlife sanctuary amid an otherwise semi-arid region of North America. Vegetation found along the river is influenced by soil type and water availability as well as by human activities, such as reservoir management, agricultural practices, and recreational uses. The North Platte River is fed by numerous, naturally occurring drainages that carry sediment and provide water at various locations as they flow into the North Platte. The North Platte originates from the Rocky Mountains in northern Colorado. It receives the majority of its water due to snowmelt, resulting in peak flows from April through July; this accounts for approximately 80% of the total annual water flow. From a hydrology perspective, streamflow forecasting for the NPRB involves formidable challenges due to the difficulties in developing an efficient physical model. Moreover, past studies have indicated the non-presence of any distinct climate signal, such as PDO, AMO, or ENSO, within the region; this indicates that the hydrologic var-