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Journal of Hydrology 325 (2006) 241–261
Journal of Hydrology
www.elsevier.com/locate/jhydrol

Predicting streamflow regime metrics for ungauged streams in Colorado, Washington, and Oregon

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Received 16 August 2004; revised 24 June 2005; accepted 6 October 2005

Abstract

Streamflow prediction in ungauged basins provides essential information for water resources planning and management and ecohydrological studies yet remains a fundamental challenge to the hydrological sciences. A methodology is presented for stratifying streamflow regimes of gauged locations, classifying the regimes of ungauged streams, and developing models for predicting a suite of ecologically pertinent streamflow metrics for these streams. Eighty-four streamflow metrics characterizing various flow regime attributes were computed along with physical and climatic drainage basin characteristics for 150 streams with little or no streamflow modification in Colorado, Washington, and Oregon. The diverse hydroclimatology of the study area necessitates flow regime stratification and geographically independent clusters were identified and used to develop separate predictive models for each flow regime type. Multiple regression models for flow magnitude, timing, and rate of change metrics were quite accurate with many adjusted R^2 values exceeding 0.80, while models describing streamflow variability did not perform as well. Separate stratification schemes for high, low, and average flows did not considerably improve models for metrics describing those particular aspects of the regime over a scheme based on the entire flow regime. Models for streams identified as 'snowmelt' type were improved if sites in Colorado and the Pacific Northwest were separated to better stratify the processes driving streamflow in these regions thus revealing limitations of geographically independent streamflow clusters. This study demonstrates that a broad suite of ecologically relevant streamflow characteristics can be accurately modeled across large heterogeneous regions using this framework. Applications of the resulting models include stratifying biomonitoring sites and quantifying linkages between specific aspects of flow regimes and aquatic community structure. In particular, the results bode well for modeling ecological processes related to high-flow magnitude, timing, and rate of change such as the recruitment of fish and riparian vegetation across large regions.

Keywords: Flow regime; Prediction; Stratification; Regression analysis; Aquatic environment; Cluster analysis

1. Introduction

Predicting streamflow behavior in ungauged (i.e. no streamflow data available) basins is a significant challenge facing the hydrologic sciences. Accurate estimates of hydrologic variables at ungauged sites

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0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2005.10.018

are not only important for water resources planning and management issues related to yield, storage, and extreme events, but are increasingly germane to ecological studies across a wide range of spatial and temporal scales. Streamflow regime encompasses the magnitude, timing, duration, and frequency of high and low flows, the rate of change of streamflow, and inter-annual variation and is increasingly cited as a 'master variable' that structures aquatic ecosystems and habitats (Poff and Ward, 1989; Richter et al., 1996; Poff et al., 1997; Baron et al., 2002). The specific hydrologic characteristics of greatest ecological relevance, however, remain largely unknown for most biotic communities. Moreover, a recent movement towards standardized biological monitoring at probabilistically selected stream and river sites (e.g. U.S. Environmental Protection Agency (USEPA), 2002) is providing unprecedented opportunities to examine biological-physical associations across broad geographic areas and hydrologic gradients. Because most biomonitoring sites are ungauged and there is substantial uncertainty regarding which hydrologic characteristics explain the observed biological variation, there is a burgeoning interest in the prediction of ecologically relevant hydrologic metrics for these sites. The need to generate a broad suite of hydrologic metrics at biological monitoring sites spanning large regions in the western United States (U.S.) provided the primary impetus for the work we present herein.

The literature is replete with studies focused on predicting selected streamflow attributes for ungauged streams (e.g. Thomas and Benson, 1970; Vogel et al., 1999; Chiang et al., 2002b). The typical approach to streamflow prediction in ungauged basins across large regions is to delineate geographic areas of similar streamflow pattern, use regression to relate watershed characteristics to streamflow variables, and assess model reliability (e.g. Jennings et al., 1994). In the western U.S., various processes control streamflow across multiple scales, hydroclimatic regions, and marked elevational gradients. The identification of distinct streamflow regime types at ungauged sites is critical for stratifying key processes and developing robust predictive models for each flow regime type. Selecting geographically contiguous regions of flow regime types from previously delineated regions (e.g. Thomas and Benson, 1970; Vogel et al., 1999) or examining residuals of regression Eqs. (Jennings et al., 1994; Tucci et al., 1995) facilitates stratification of ungauged streams. Cluster analysis can be used to objectively define geographically independent streamflow groups across regions (Hawley and McCuen, 1982; Haines et al., 1988; Burn, 1989; Hughes and James, 1989; Poff and Ward, 1989; Burn and Boorman, 1993; Kresch, 1993; Poff, 1996; Harris et al., 2000) and has been coupled with discriminant analysis to identify streamflow cluster membership of ungauged streams using catchment characteristics (Chiang et al., 2002a,b). Regression has been used within defined regions or strata to predict the mean and variance of flows, autocorrelation, flood durations and volumes (Thomas and Benson, 1970), parameters of statistical distributions to reproduce flow duration curves (e.g. Smakhtin et al., 1997; Fennessey and Vogel, 1990; Sugiyama et al., 2003), direct estimates of flood quantiles (Thomas and Benson, 1970; Surian and Andrews, 1999; Pitlick, 1994; Jennings et al., 1994), low flows (Ries and Friesz, 2000), and parameters of time series models to generate synthetic streamflows (Chiang et al., 2002a,b). Flow duration curves and flood quantile estimates provide valuable information about flow magnitudes and frequencies but cannot provide information about timing, a critical variable in many ecological studies. Synthetic monthly streamflows generated from a time series model include timing but omit information contained in metrics which characterize flows at the event or daily time scale.

In this paper, our purpose is to present: (1) a validated stratification scheme for identification and subsequent classification of streamflow regime types for ungauged sites, and (2) models developed for providing accurate estimates of a broad range of streamflow metrics of ecological interest at ungauged biological monitoring sites in 18 ecoregions (Omernik, 1995) of Colorado (CO), Oregon (OR), and Washington (WA). The disconnectedness and acute hydroclimatic variability of the study region and the prediction of unique streamflow metrics characterizing the entire flow regime provide practical insights regarding the efficacy of streamflow prediction for ecological studies across heterogeneous areas. In addition, we examine the utility of using different clustering schemes for high, low, and average flows and the effects of grouping streams with similar