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Monthly paleostreamflow reconstruction from annual tree-ring chronologies

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ABSTRACT

Paleoclimate reconstructions are increasingly used to characterize annual climate variability prior to the instrumental record, to improve estimates of climate extremes, and to provide a baseline for climate-change projections. To date, paleoclimate records have seen limited engineering use to estimate hydrologic risks because water systems models and managers usually require streamflow input at the monthly scale. This study explores the hypothesis that monthly streamflows can be adequately modeled by statistically decomposing annual flow reconstructions. To test this hypothesis, a multiple linear regression model for monthly streamflow reconstruction is presented that expands the set of predictors to include annual streamflow reconstructions, reconstructions of global circulation, and potential differences among regional tree-ring chronologies related to tree species and geographic location. This approach is used to reconstruct 600 years of monthly streamflows at two sites on the Bear and Logan rivers in northern Utah. Nash-Sutcliffe Efficiencies remain above zero (0.26–0.60) for all months except April and Pearson's correlation coefficients (R) are 0.94 and 0.88 for the Bear and Logan rivers, respectively, confirming that the model can adequately reproduce monthly flows during the reference period (10/1942 to 9/2015). Incorporating a flexible transition between the previous and concurrent annual reconstructed flows was the most important factor for model skill. Expanding the model to include global climate indices and regional tree-ring chronologies produced smaller, but still significant improvements in model fit. The model presented here is the only approach currently available to reconstruct monthly streamflows directly from tree-ring chronologies and climate reconstructions, rather than using resampling of the observed record. With reasonable estimates of monthly flow that extend back in time many centuries, water managers can challenge systems models with a larger range of natural variability in drought and pluvial events and better evaluate extreme events with recurrence intervals longer than the observed record. Establishing this natural baseline is critical when estimating future hydrologic risks under conditions of a non-stationary climate.

1. Introduction

While grappling with the question of how future climate changes will affect the likelihood and severity of hydrological extremes (floods and droughts), hydrologists, engineers, and water-resources planners have noted the potential for streamflow reconstructions to characterize pre-industrial hydrologic variability over multiple centuries (Bonin and Burn, 2005). By combining reconstructions of the past with climate change projections, it may be possible to place the signal of climate change-induced streamflow trends in the context of long-term natural variability. In addition, streamflow reconstructions can significantly increase the number of scenarios used for drought vulnerability studies or water resources systems optimization. Despite these potential benefits, streamflow reconstructions have not gained widespread use in water systems analysis, in part because flow has typically been reconstructed at an annual resolution, which is generally too coarse for analysis of drought vulnerability and decision-making. This study explores whether monthly streamflows can be adequately predicted from annual tree-ring chronologies and other reconstructed data. To confirm this, we outline and test a novel statistical method to reconstruct monthly flow series.

Existing techniques for annual streamflow reconstruction primarily rely on linear regression to relate carefully chosen tree-ring chronologies to mean annual flow (MAF) during the available

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instrumental record. This relationship is then applied to the full tree-ring record to reconstruct flows outside the observed period (Loaiciga et al., 1993; Cook and Kairiukstis, 2013). Tree-ring chronologies are carefully developed by selecting sites and species in which the reconstruction variable is the limiting factor for tree growth. Multiple replication samples are often taken for each tree and these measurements across many trees at a given site are combined to generate a master site ring width, through a process called crossdating, whereby common features in the chronology are matched (Fritts, 2012; Douglass, 1941). The resulting chronologies can be linked to climate variables either through simple linear regression (Duvick and Blasing, 1981), multiple linear regression (Meko et al., 1980), or more complex approaches.

More complex reconstruction approaches often rely on Principal Component Analysis (PCA) to extract differences/commonalities across multiple site chronologies and tree species to better capture regional variations (Cook et al., 1994; Hidalgo et al., 2000; Maxwell et al., 2011) or seasonal effects (Brubaker, 1980). Meko et al. (2015) showed that flow reconstruction accuracy can be improved by using PCA and regression to combine chronologies from traditional reconstruction species and less traditional species which capture unique climate signals.

Reconstruction approaches assume that processes relating climate to tree-ring growth during the instrumental record are identical to the reconstructed period (Fritts, 2012). This Principle of Uniformatism has been slightly modified in modern dendrochronology to separate the important climate signal from underlying factors affecting tree growth (Cook, 1987). Uniformitism is particularly important for flow reconstructions, where river reaches should be selected to avoid significant man-made effects. Alternatively, the effects of impoundments or land use change can be removed from the time series to approximate a near-natural flow record. Annual streamflow recontructions have been produced for regions with adequate tree-ring chronologies (Meko et al., 2001; Woodhouse et al., 2006) and have been used for water resources planning, e.g. Woodhouse and Lukas (2006) and Axelson et al. (2009).

Despite the availability of annual streamflow reconstructions, few methodologies currently exist to reconstruct sub-annual flow from annual resolved tree-ring chronologies (Gangopadhyay et al., 2015; Sauchyn and Ilich, 2017). The Sauchyn and Ilich (2017) approach uses stochastic hydrology techniques to generate many feasible sequences of weekly flows that sum to the annual reconstruction while maintaining statistical properties of the observed record. The Gangopadhyay et al. (2015) approach instead resamples annual subsets of temperature and precipitation from the instrumental records and matches them to tree-ring widths in the paleo-record using a K-nearest neighbor approach repeated many times to develop an ensemble of temperature and precipitation timeseries (Gangopadhyay et al., 2009). Temperature and precipitation are then used as inputs for a water balance model (Wolock and McCabe, 1999). This method has been used to generate seasonal streamflow in Nevada (Solander et al., 2010) and monthly streamflow along the Colorado River (Gangopadhyay et al., 2015). While useful for generating runoff in well-studied watersheds, this approach requires a calibrated watershed model that is not always available. Additionally, by resampling from the observed record, the potential monthly time series of temperature and precipitation are limited to re-ordering ≈60–100 observed annual subsets from the instrumental record. While this may be an effective approach for some locations, it is highly desirable to develop methods to reconstruct monthly streamflow directly, without the need for watershed models and the limitations of repeated resampling.

To test the hypothesis that monthly streamflow can be reconstructed from annual tree-ring chronologies, this study introduces a novel approach for reconstructing monthly streamflow that extends fundamental principles of flow reconstruction and then demonstrates these models by reconstructing flow and evaluating goodness of fit for two sites in northern Utah. The candidate models include a simple Monthly Fraction (MF) model, an Annual Percentile (AP) model that directly links annual flow percentile with monthly percentile, and an Annual Percentile with Regression (APR) model that uses multiple annual reconstructions to predict the monthly percentile. Several versions of the APR model are considered, each adding increasing predictors which include: 1) the original annual streamflow reconstructions; 2) climate reconstructions of the El Niño-Southern Oscillation (ENSO); and 3) regionally available tree-ring chronologies. Regional tree-ring chronologies were included as predictors based on the hypothesis that different species, elevations, and site locations might capture different parts of the seasonal hydrologic signal, whereas ENSO was considered because it has shown coherence with streamflow and precipitation in the western U.S. and Utah (Cayan et al., 1999; Schoennagel et al., 2005; Wang et al., 2012; DeFlorio et al., 2013; Zhou et al., 2014). The paper further evaluates and discusses model results in the context of individual predictors, their physical basis, and implications for water management.

2. Models

Three model frameworks are introduced in this study as potential candidates for the reconstruction of mean monthly streamflow. The MF model uses simplistic assumptions to reconstruct monthly streamflows and is included as a "null" model, against which the other models can be compared. The remaining two models constitute the primary approach proposed herein and are presented in order of increasing complexity, each applying the same basic framework, but with increasing numbers of predictors. First, the AP model directly links the reconstructed annual streamflow percentiles to monthly percentiles, using the assumption that the monthly percentile is constant and identical to the reconstructed annual percentile throughout each water year. Second, the APR model estimates monthly percentiles using regression, first considering only lagged annual streamflow percentiles and ultimately incorporating additional predictors such as global climate indices (ENSO) or spatial/species patterns in regional tree-ring chronologies extracted by PCA. The models and fitting procedures are available as an R package, paleoAPR (Stagge, 2017), while the code and data for the specific analyses performed in this paper are available in an online repository athttps://doi.org/10.5281/zenodo.1029739.

2.1. Monthly fraction (MF) model

The MF model assumes that the monthly proportion of total annual streamflow (TAF) is identical across all years. Based on this assumption, the monthly fraction, $\bar{f}_{m,y}$, is determined for each month by dividing the monthly flow volume, $Q_{m,a}$, by annual volume, TAF_y. In this notation, "m" and "a" subscripts correspond to monthly and annual steps, respectively. TAF is equivalent to $12 \times MAF$. Monthly streamflow is then reconstructed by multiplying the appropriate mean monthly fraction, $\bar{f}_m$, for each of the 12 months by reconstructed TAF:

$$\widehat{Q}_m = \bar{f}_m \times TAF_a, \quad \text{where} \quad \bar{f}_m = \frac{\sum_{a=1}^{n} f_{m,y}}{n} \quad \text{and} \quad f_{m,a} = \frac{Q_{m,a}}{TAF_a} \qquad (1)$$

where $\widehat{Q}_m$ represents estimated monthly streamflow. Monthly flows reconstructed by the MF model retain the same seasonal shape, but are scaled linearly. For example, if an average of 30% of each year's historical flow volume occurred during June, this proportion is maintained in the reconstruction. Prior to performing