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Ensemble streamflow prediction adjustment for upstream water use and regulation

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SUMMARY

Hydrologic model forecasts are commonly biased in watersheds where water use and regulation activities cause flow alterations. Furthermore, direct accounting of such biases in forecast preparation is impractical as the information required is extensive and usually unavailable. This article introduces a new method to characterize the aggregate flow alteration biases and associated uncertainty in watersheds with important but largely undocumented water use and regulation activities. It also uses these assessments to adjust the ensemble streamflow predictions at downstream locations. The method includes procedures to (a) detect the presence of significant upstream regulation and water use influences; (b) correct the ensemble streamflow predictions and associated uncertainty for any biases in periods when such influences are detectable; and (c) assess the adjusted forecast reliability improvements. Applications in three watersheds of the American River in California demonstrate that the new method leads to significant forecast skill improvements and is also readily applicable to other regions.

1. Introduction

In watersheds with appreciable water use and regulation (including storage reservoirs, in-stream withdrawals, and/or inter-basin water transfers), the development of reliable Ensemble Streamflow Predictions (ESP) at downstream locations requires characterization and incorporation of the expected streamflow alterations from natural conditions and their associated uncertainty. Streamflow alterations can be incorporated if, as part of the ESP forecast generation process, water use and regulation activities are represented with sufficient accuracy. This approach can be effective in watersheds where flow alterations occur due to large, main stem river projects and well documented water use activities, but it becomes impractical where flow alterations result from many small and/or medium scale storage projects and water use activities distributed throughout the watershed. In the latter cases, comprehensive information on reservoir filling and depletion, water withdrawals and returns, and/or water transfers is both not readily available and subject to change from year to year, adding bias and uncertainty to the flow forecasts. This article introduces procedures to characterize the aggregate flow alteration biases and uncertainty in watersheds in the latter category and incorporate them in ensemble streamflow predictions at downstream points. The research follows recent National Research Council recommendations for making hydrometeorological forecasts more valuable for decision makers (e.g., NRC, 2006). The value of reliable uncertainty measures for downstream regulation has been shown in several earlier studies of the authors (e.g., Graham and Georgakakos, 2010; Georgakakos and Graham, 2008; Georgakakos and Krzysztofowicz, 2001; Georgakakos et al., 1998; Yao and Georgakakos, 2001; Kistenmacher and Georgakakos, in preparation).

The approach includes procedures to (a) detect the presence of significant upstream regulation and water use influences; (b) correct the ensemble streamflow predictions and associated uncertainty for any biases during periods when upstream regulation and water use influences are detected; and (c) assess the forecast reliability improvements. Validation results are reported for three California watersheds. The forecast adjustment approach has been developed for operational use in routine forecast operations of the U.S. National Weather Service River Forecast Centers.

The following sections describe the modeling framework, case study basins and available hydrologic and forecast data, procedure to detect whether upstream storage effects and transfers are significant, models used to account for upstream water use and

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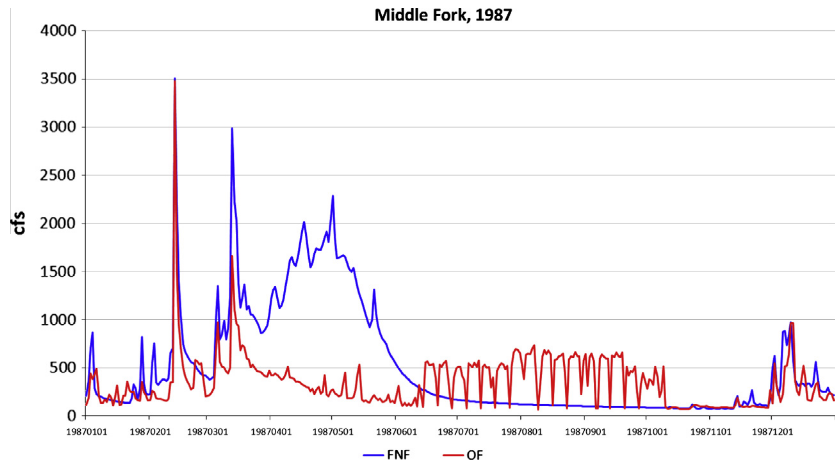

Fig. 1. Comparison of unimpaired and observed outflows; Middle Fork, 1987.

regulation influences and bias adjustment, and validation results for three watersheds of the American River in California. The article concludes with a summary of research findings and recommendations.

2. Typical data and modeling framework

The need for forecast modification comes about because of the cumulative flow alteration that distributed water uses (within a watershed) exert on watershed outflow. Typical water uses may include water supply for irrigation, domestic, or industrial use; small hydro-plant operation; and low flow augmentation for environmental and ecosystem sustainability. Some of the uses are consumptive, having direct impact on the quantity of available water, while others modify the timing of the natural flows. Our approach addresses situations where such water uses are enabled by (a) direct water withdrawals and use without storage facilities, (b) water transfers in or out of the watershed, and (c) several small and/or medium size storage facilities distributed across the watershed. Watersheds in which seasonal or over-year water use and regulation occurs primarily at a few major storage facilities or other water works can also be addressed, but this approach is not expected to be as effective as detailed simulation of the physical plants and regulation procedures Figs. 1 and 2 show the unimpaired (blue[3] line) and observed daily outflows (red line) for a typical year at the outlets of the Middle and North Fork watersheds on the American River (California). The unimpaired flow (also referred to as full natural flow) data series represents watershed outflow that would have occurred in the absence of upstream water use and regulation, and it is usually generated by hydrologic models driven by observed precipitation and evapotranspiration sequences. Unimpaired flows can also be reconstructed from observed flows by adding back known net water withdrawals and regulation effects.

These figures illustrate (a) the type of information that is generally available for assessing the presence of upstream regulation and (b) the need for a general modeling approach applicable to watersheds with and without apparent upstream regulation. Typically, the available information includes:

- Daily or sub-daily flow observations at the watershed outlet.
- Unimpaired watershed outflow sequences, either model generated (based on contemporaneous data of watershed precipitation, temperature, evapotranspiration, and flow) or reconstructed from observed outflows and knowledge of existing water uses.
- Anecdotal or quantitative information (obtained by water agencies and other stakeholders) on the nature, timing, and quantities of water uses and transfers (be they exports or imports), release rules for some of the existing storage facilities, and instream flow requirements.

[3] For interpretation of color in Figs. 1, 2, 6 and 7, the reader is referred to the web version of this article.

The approach described herein aims to be widely applicable and relies primarily on the first two information categories. If available, information of the third category can be used to further ascertain and validate the exploratory data analysis.

Furthermore, Figs. 1 and 2 show that forecast adjustment can be beneficial for watersheds with and without upstream regulation. The North Fork watershed in Fig. 2 exemplifies a case without obvious upstream regulation effects, while the Middle Fork watershed in Fig. 1 clearly exhibits significant seasonal regulation.

As mentioned earlier, upstream regulation may also include flow alterations that do not entail storage regulation such as direct water use, imports, and/or exports. Such alterations become part of the biases between observed and "natural" outflows and are not easily distinguishable. In such cases, Regression and/or Neural Network models are well suited for bias removal and forecast correction (Wilks, 2006).

The watershed of Fig. 1 exhibits three distinct time periods: a spring storage filling period where unimpaired flows consistently exceed observed flows, a summer storage release period where observed flows are clearly augmented with respect to unimpaired flows, and the rest of the year where observed and unimpaired flows are not appreciably different. In such watersheds, the extent and duration of flow augmentation depends on the available aggregate storage, which, in turn, depends on the antecedent hydrologic conditions. This type of dynamic flow alteration involves more than seasonal flow biases and cannot be fully captured by Regression and Neural Network models. In this work, such cases are handled by an aggregate storage model calibrated to represent the watershed storage filling and depletion process and the transfer of water from the wet to the dry season. Regression and Neural Network models are still potentially useful in the third period, where storage regulation effects are insignificant.

Thus, the proposed modeling framework is designed to utilize different modeling approaches depending on the existing upstream regulation type and time of the year. Fig. 3 schematically summarizes the modeling framework logic and main components. The modeling framework includes (i) testing for the existence, if