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Regionalization of hydrologic response in the Great Lakes basin: Considerations of temporal scales of analysis

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SUMMARY

Methods for predicting streamflow in areas with limited or nonexistent measures of hydrologic response commonly rely on regionalization techniques, where knowledge pertaining to gauged watersheds is transferred to ungauged watersheds. Hydrologic response indices have frequently been employed in contemporary regionalization research related to predictions in ungauged basins. In this study, we developed regionalization models using multiple linear regression and regression tree analysis to derive relationships between hydrologic response and watershed physical characteristics for 163 watersheds in the Great Lakes basin. These models provide an empirical means for simulating runoff in ungauged basins at a monthly time step without implementation of a rainfall–runoff model. For the dependent variable in these regression models, we used monthly runoff ratio as the indicator of hydrologic response and defined it at two temporal scales: (1) treating all monthly runoff ratios as individual observations, and (2) using the mean of these monthly runoff ratios for each watershed as a representative observation. Application of the models to 62 validation watersheds throughout the Great Lakes basin indicated that model simulations were far more sensitive to the temporal characterization of hydrologic response than to the type of regression technique employed, and that models conditioned on individual monthly runoff ratios (rather than long term mean values) performed better. This finding is important in light of the increased usage of hydrologic response indices in recent regionalization studies. Models using individual observations for the dependent variable generally simulated monthly runoff with reasonable skill in the validation watersheds (median Nash–Sutcliffe efficiency = 0.53, median R^2 = 0.66, median magnitude of the deviation of runoff volume = 13%). These results suggest the viability of empirical approaches to simulate runoff in ungauged basins. This finding is significant given the many regions of the world with sparse gauging networks and limited resources for gathering the field data required to calibrate rainfall–runoff models.

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1. Introduction

1.1. Predictions in ungauged basins

Addressing water quantity and quality issues is possible in gauged basins using rainfall–runoff models calibrated to streamflow observations. The need to address these issues over spatial domains with limited or nonexistent stream gauge observation networks motivated the International Association of Hydrological Sciences Prediction in Ungauged Basins (PUB) Initiative (Sivapalan et al., 2003; Hrachowitz et al., 2013). While PUB research is typically conducted at local or regional scales, the challenges of understanding hydrological processes in data sparse locations are global. In fact, the least developed gauging networks are generally found in those regions most susceptible to hydrologic impacts from expanding populations and changes in land use and climate (Sivapalan et al., 2003).

Traditional approaches to the PUB problem involve determining an appropriate parameter set for a rainfall–runoff model structure for application in the ungauged basin. Without the aid of streamflow observations for estimating these parameters, PUB research commonly employs regionalization techniques to establish relationships between gauged and ungauged watersheds (Vogel, 2006; Wagener et al., 2004). A variety of regionalization

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approaches have been developed for estimating parameter sets at ungauged sites. For example, a parameter set may be inferred for an ungauged watershed based on its spatial proximity or physical similarity to gauged watersheds (McIntyre et al., 2005; Nijssen et al., 2001; Parajka et al., 2005; Reichl et al., 2009). Alternatively, parameter sets may be estimated at the ungauged site based on statistical relationships between calibrated parameters and watershed physical characteristics (Abdulla and Lettenmaier, 1997; Post, 2009; Post and Jakeman, 1999; Sefton and Howarth, 1998; Seibert, 1999). Frequently, these regionalization approaches are explored in tandem (Kokkonen et al., 2003; Merz and Blöschl, 2004; Samuel et al., 2011).

Regionalization techniques tied to rainfall–runoff model structures have been met with a variety of practical and theoretical challenges. For example, the suitability of a regionalization approach is both location specific (Bao et al., 2012; Beven, 2000; Oudin et al., 2008; Wagener and Wheater, 2006) and rainfall–runoff model specific (Bárdossy, 2007; Beven, 2006; Kay et al., 2006). In response to the uncertainties introduced in model-dependent regionalization approaches, recent studies developed regionalization schemes that are model-independent (that is, they can be applied to any rainfall–runoff model). Wagener and Montanari (2011) review emerging methods wherein model-independent measures of hydrologic response in gauged watersheds (rather than direct streamflow observations) are employed to establish a regionalization scheme. A wealth of indices has been derived to implicitly quantify these processes (Olden and Poff, 2003). Examples include watershed input–output relationships (e.g. runoff ratio), hydrograph analytics (e.g. rising limb density) and metrics characterizing the magnitude, frequency, duration and timing of flow events (e.g. baseflow index and flood frequency).

Yadav et al. (2007) presented a rainfall–runoff model-independent approach to making predictions in ungauged basins based on empirical relationships between watershed physical characteristics and a variety of hydrologic response indices. Three response indices (runoff ratio, high pulse count, and the slope of the flow duration curve) were shown to be useful for constraining ensemble predictions at ungauged sites. Shamir et al. (2005) developed two hydrograph-based response indices (rising and declining limb density) to improve the identification of optimal parameters for a process-based rainfall–runoff model; a case study employing this method indicated improved model reliability and predictive skill. Sawicz et al. (2011) developed a classification scheme for watersheds in the eastern U.S. that incorporated six hydrologic response indices observed to vary along a climate gradient: runoff ratio, baseflow index, snow day ratio, slope of the flow duration curve, streamflow elasticity, and the rising limb density.

Relationships between hydrologic response indices and watershed physical characteristics are typically used to provide ancillary information for rainfall–runoff modeling. For example, Bulygina et al. (2009) used this information to constrain the range of allowable values for model parameters. Alternatively, this information can be used to develop an ensemble of predictions based on the likelihoods of candidate models (McIntyre et al., 2005; Reichl et al., 2009). Finally, some hydrologic response indices (e.g. runoff ratio) can be applied directly to simulate runoff in ungauged watersheds, as is demonstrated in this study. This approach is rainfall–runoff model-independent in the sense that a process-based model is not implemented.

Hydrologic response indices have traditionally been developed to describe a watershed's typical behavior over a given period of time. For example, runoff ratio, also referred to as runoff yield, is a dimensionless index obtained by dividing total basin runoff by total basin precipitation over an equivalent time period. Yadav et al. (2007) defined runoff ratio as average annual runoff divided by average annual precipitation. Berger and Entekhabi (2001) and Sawicz et al. (2011) defined it more generally as the ratio of long-term runoff to long-term precipitation. Similarly, nearly all of the 171 response indices reviewed by Olden and Poff (2003) are derived as long-term mean values, representing the average watershed behavior over a given time period. Moreover, despite the fact that hydrologic response can exhibit substantial seasonal variability (see Section 4), runoff ratio has typically been defined at an annual time step. As a result, contemporary research utilizing hydrologic response indices has addressed the spatial, but not temporal, variability in watershed behavior.

This research gap is addressed by developing and regionalizing two different temporal characterizations of runoff ratio at a monthly time step, addressing the research question of how both interannual and seasonal temporal variability in hydrologic response affects predictions in ungauged basins. Specifically, the objectives of this study are to:

- Develop regression-based regionalization models between watershed physical characteristics and monthly runoff ratio as an index of hydrologic response.
- Use the models to simulate streamflow in ungauged basins at a monthly time scale without implementation of a rainfall–runoff model.
- Illustrate the effects of defining hydrologic response at different temporal scales (long-term average versus short-term indices) in terms of model skill and applicability to water resource management objectives.
- Assess the potential for regression tree models for hydrologic modeling alongside a commonly used multiple linear regression model.

1.2. Hydrologic modeling in the Great Lakes basin

We address our research objectives in the Great Lakes basin. The Great Lakes basin (Fig. 1) drains over half a million square kilometers of land in the United States and Canada featuring varied land cover, climate, subsurface characteristics, and human activity. Fig. 1 shows dominant land cover type throughout the basin by U.S. Geological Survey (USGS) 12-digit hydrologic unit code (HUC12) delineations (USGS, 2012). The basin is home to over 30 million residents, many of whom live in highly urbanized areas adjacent to the lakes. Temperature and precipitation variability is a function of both latitudinal and lake effects (Choi et al., 2012; Norton and Bolsenga, 1993). Significantly different subsurface properties exist throughout the basin as a result of the geologic formation of the Great Lakes. At the scale of the Great Lakes basin, this variability results in a wide range of potential hydrologic response among watersheds, both gauged and ungauged.

Predictions in ungauged portions of the Great Lakes basin are essential for research and management objectives related to the effects of land use/land cover change on near-shore ecosystems (Wolter et al., 2006); nonpoint source pollution loadings (He and DeMarchi, 2010); net water supply availability for irrigation, hydropower, and human consumption (Changnon, 1987; He, 1997), and lake level forecasting to support the needs of transportation and recreation industries (Gronewold et al., 2011; Lee et al., 1997). In recent years, the need to reduce uncertainty in each of the components of the Great Lakes basin water budget has become increasingly clear due to dramatic changes in water level dynamics (Gronewold and Stow, 2014). Complete spatial coverage of runoff estimates throughout the Great Lakes basin is critical for preparing reliable water level forecasts and for understanding the mechanisms involved in fluctuating water levels. A number of recent workshops and regional studies have resulted in recommendations to improve basin-wide runoff estimates (Coon et al., 2011; Fry et al., 2013; Gronewold and Fortin, 2012; Gronewold et al., 2011).

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