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Geospatial tools effectively estimate nonexceedance probabilities of daily streamflow at ungauged and intermittently gauged locations in Ohio

William H. Farmer[a,*], G.F. Koltun[b]

[a] U.S. Geological Survey, Denver, CO, USA
[b] U.S. Geological Survey, Columbus, OH, USA

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ABSTRACT

Study region: The state of Ohio in the United States, a humid, continental climate.
Study focus: The estimation of nonexceedance probabilities of daily streamflows as an alternative means of establishing the relative magnitudes of streamflows associated with hydrologic and water-quality observations.
New hydrological insights for the region: Several methods for estimating nonexceedance probabilities of daily mean streamflows are explored, including single-index methodologies (nearest-neighboring index) and geospatial tools (kriging and topological kriging). These methods were evaluated by conducting leave-one-out cross-validations based on analyses of nearly 7 years of daily streamflow data from 79 unregulated streamgages in Ohio and neighboring states. The pooled, ordinary kriging model, with a median Nash–Sutcliffe performance of 0.87, was superior to the single-site index methods, though there was some bias in the tails of the probability distribution. Incorporating network structure through topological kriging did not improve performance. The pooled, ordinary kriging model was applied to 118 locations without systematic streamgaging across Ohio where instantaneous streamflow measurements had been made concurrent with water-quality sampling on at least 3 separate days. Spearman rank correlations between estimated nonexceedance probabilities and measured streamflows were high, with a median value of 0.76. In consideration of application, the degree of regulation in a set of sample sites helped to specify the streamgages required to implement kriging approaches successfully.

1. Introduction

Prediction or estimation of unmeasured hydrologic phenomena is a common objective of hydrologic sciences. So much so, that the International Association for Hydrological Sciences recently dedicated an entire decade to focused research on streamflow estimation in ungauged basins (Sivapalan et al., 2003; Blöschl et al., 2013). The need for widespread streamflow data has become increasingly more pressing as the human population has expanded, yet the majority of our planet remains hydrologically ungauged (e.g. as Kiang et al., 2013 in the United States). With these thoughts in mind, this work demonstrates how a new tool for hydrologic estimation can be leveraged to advise the management of water resources.

Most methods of hydrologic estimation in ungauged basins are focused on modeling of streamflow time series (e.g., see Parajka et al., 2013; Farmer et al., 2014; Farmer, 2015 for a description of many alternatives) or prediction of streamflow quantiles

* Corresponding author.
E-mail address: wfarmer@usgs.gov (W.H. Farmer).

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(Castellarin et al., 2013; Pugliese et al., 2016). Occasionally, a streamflow time series is not required to meet the particular needs of a study. For example, between 2009 and 2015 the Ohio Environmental Protection Agency (OEPA) collected water-quality samples at hundreds of sites across the state. Most of these sites were sampled only a handful of times and the sites were not typically located at or near gauged locations. Though streamflow was measured by the OEPA when some samples were collected, since streamflow data were not always necessary to meet OEPA's original data objectives, the majority of samples had no associated streamflow data. However, a new use for the sampled data has arisen in which proper interpretation requires that the individual sample results be given a hydrologic context. While estimates of streamflows associated with the samples would be most useful, it is simpler and less costly to provide that hydrologic context by estimating streamflow nonexceedance probabilities. Having estimates of streamflow nonexceedance probabilities, for example, permits sample results to be binned or classified as being associated with high, medium, or low streamflows.

One of the most common approaches to the consideration of hydrologic context looks at the distribution of daily streamflows, commonly called the flow duration curve (FDC). FDCs describe the relation between streamflows and the percentage of time those streamflows were equaled or exceeded over some period. As pointed out by Castellarin (2014), statistical hydrologists might refer to an FDC as the exceedance probability function of streamflow. Searcy (1959) and Vogel and Fennessey (1995) provided extensive discussion on applications of FDCs and much research has been done to evaluate different techniques for estimating FDCs at ungauged stream sites (e.g. Castellarin et al., 2004; , 2013; Booker and Snelder, 2012; Mendicino and Senatore, 2013; Muüller and Thompson, 2016; Atieh et al., 2017). Techniques for estimating FDCs at ungauged sites historically have involved using regional information to estimate the parameters of a statistical distribution that fits the FDC or index flow methods in which a standard curve is predicted which is subsequently scaled by an index flow that also is predicted. More recently, various forms of kriging, or spatial interpolation, have been used in the FDC estimation process (e.g. Castellarin, 2014; Pugliese et al., 2016).

Although FDCs have a wide range of uses, there may be times, as mentioned earlier, when it is sufficient to know the exceedance probability of the streamflow on a given day without going to the effort and expense of determining the streamflow magnitude. For example, concentrations of many constituents that are transported in streams tend to increase or decrease as a function of streamflow magnitude. So, for example, if one were to compare concentrations obtained over time, it is useful to be able to distinguish between times when streamflows were low versus when streamflows were high. If streamflow exceedance probabilities can be associated with observed concentrations, that provides a hydrologic context for the observed concentrations and permits discretization of concentrations into different categories of streamflow (e.g., high, medium, or low). That discretization can be useful in qualitative and quantitative analyses (e.g., comparison tests, analysis of variance, etc.).

Hydrologic kriging is one of the newer tools for estimating hydrologic phenomena at ungauged locations (Sauquet, 2006; Skøien et al., 2006; Skøien and Blöschl, 2007; Archfield and Vogel, 2010; Farmer et al., 2014; Farmer, 2016), but hydrologic mapping, which similarly considers the spatial variation in observed hydrologic data, has a much longer history (Langbein, 1949; Busby, 1963; Langbein and Slack, 1982). In the United States, hand-drawn maps of annual runoff and flood probabilities can be traced back more than 100 years (Langbein, 1949), and even earlier examples exist from Europe and Asia. Automated methods for mapping some hydrologic phenomena were developed as computers became more common and accessible (Langbein and Slack, 1982). Kriging, a geostatistical technique developed in the mining industry (Skøien et al., 2006), is one of the newer methods being applied to hydrology, and in particular, streamflow estimation. Farmer (2015) suggested that, in addition to estimating streamflows, it may be possible to use kriging to model the spatial structure of streamflow exceedance or nonexceedance probabilities.

This work, expanding the exploration of geostatistical tools for hydrologic applications, hypothesizes that recent advances in hydrologic kriging (Farmer, 2016) can be used to predict the ranking of streamflow on a given day at an ungauged location. Rather than producing streamflow estimates, these tools are used to approximate the hydrologic plotting position at the ungauged location by estimating the nonexceedance probability of streamflow on the day of interest. Several methods were considered and evaluated. Pooled, ordinary kriging, a tool for geospatial interpolation, is compared with single-index alternatives. A brief discussion of topological kriging, an alternative geospatial method is also included. After cross validating these methodologies on unregulated streams, a unique application of the approach was made to intermittently sampled water quality sites, with some analysis of performance and a consideration of possible effects of regulation. The conclusion is a final application of the ideal model to the region of interest.

2. Material and methods

2.1. Study area and streamflow data

The study area includes the entire state of Ohio, which covers an area of approximately 116,099 km^2. Based on a classification of land cover from Landsat satellite data circa 2011 (Homer et al., 2015), agriculture was the dominate land cover in Ohio comprising more than 46% of the state followed by forest (28.5%) and developed (13.5%) land covers. Open water (not including wetlands) covered about 8.9% of Ohio. Ohio has more than 96,560 km of streams (Sanders, 2001).

Ohio has a humid continental climate characterized by large seasonal temperature changes and generally ample precipitation derived from both frontal and convective storms. Between 2009 and 2015, statewide annual average temperatures ranged from 9.6 to 12.2 °C and statewide average annual rainfall totals ranged from 92.7 to 142.1 cm (NOAA National Centers for Environmental and Information, 2016). By comparison, the average annual temperatures and rainfall totals for Ohio for the 30-year period from 1971 to 2000 were 10.3 °C and 99.2 cm, respectively (NOAA National Centers for Environmental and Information, 2016).

Daily mean streamflow data for the period from 01 January 2009 to 31 August 2015 were obtained from the USGS NWISWeb site (http://dx.doi.org/10.5066/F7P55KJN) for 126 streamgages in Ohio and 26 streamgages in neighboring states (Fig. 1). This time