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Posterior assessment of reference gages for water resources management using instantaneous flow measurements

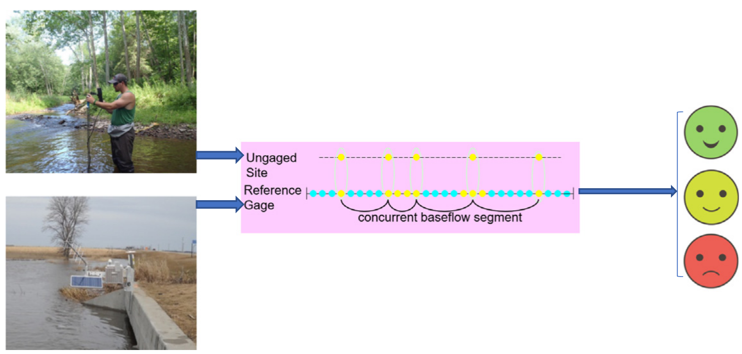
Can Liu [a], Zhenxing Zhang [b,*], John Wassil Balay [a]

[a] Susquehanna River Basin Commission, 4423 N Front St., Harrisburg, PA 17110, USA
[b] Illinois State Water Survey, Prairie Research Institute, University of Illinois at Urbana-Champaign, Champaign, IL 61820, USA

HIGHLIGHTS

- Propose an approach to assess reference gages using flow measurements
- Test the approach with 18 real-world water resources management sites
- The approach is economically feasible, as only 10 flow measurements may be needed

GRAPHICAL ABSTRACT



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ABSTRACT

Reference stream gages are commonly used for a variety of hydrologic studies and water resources management purposes. Reference gage selection methods have been extensively investigated in literature. However, the posterior assessment of reference gages is a long-standing challenge faced by water resources managers. This study aims to evaluate the accuracy of using reference gages in estimating low flow conditions at ungaged sites. The proposed assessment method is comprised of three fundamental components including: (1) a field campaign to obtain instantaneous flow measurements at ungaged sites during baseflow conditions; (2) streamflow correlation and streamflow ratio analyses using field measured values at ungaged sites and concurrent reference gage data; and (3) map correlation analysis to identify alternative reference gages for ungaged sites with undesirable flow correlation and flow ratio values. The method was tested using 18 systematically selected reference gages used by the Susquehanna River Basin Commission for regulating water withdrawals and ensuring compliance with passby flow requirements. Streamflow monitoring during baseflow conditions over the course of four consecutive low flow seasons resulted in the collection of ten streamflow measurements for each ungaged site. The streamflow correlation coefficients between streamflow measurements at ungaged sites and concurrent reference gage streamflow data were found to be greater than 0.7 for 17 of the 18 sites. Map correlation analysis was conducted to identify alternative reference gages for three ungaged sites which exhibited high prediction errors or low streamflow correlation. The case study demonstrates that proposed posterior assessment method for evaluating reference gage performance is easy to use with reasonable cost.

* Corresponding author.
E-mail address: zhang538@illinois.edu. (Z. Zhang).

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1. Introduction

Streamflow statistics and flow duration curves (FDC) (Stedinger, 1993; Yuan, 2013; Zhang, 2017) are commonly used in water resources planning and management practices (Smakhtin, 2001; Chen et al., 2007; Bangash et al., 2012; Zhang and Balay, 2014; Zhang and Kroll, 2007a). For a streamflow gage where reliable long-term continuous streamflow records are available, the needed streamflow statistics could be accurately estimated via a frequency analysis, providing sound basis for water resources planning and management (Zhang and Kroll, 2007b). However, water resources projects or water uses are more often located at ungaged sites where streamflow is not monitored and thus, long-term streamflow records could not be obtained. Water resources managers are confronted with the task of estimating streamflow for ungaged sites to best manage water resources.

For prediction in ungaged basins (PUB), the use of a reference gage (also known as an index gage, donor gage, or base station) is generally required, which is assumed to be hydrologically similar to the ungaged site of interest under the premise of similar geologic, topographic, and climatic settings (Sivapalan, 2003; Sivapalan et al., 2003). A wide range of methods existed to estimate streamflow statistics for ungaged sites, such as regional regression (Pandey and Nguyen, 1999; Thomas and Benson, 1970; Vogel et al., 1999; Stagnitta et al., 2018), rainfall-runoff model (Liu and Gupta, 2007; Zhang et al., 2008; Wagener et al., 2009; Mas-Pla et al., 2012; Liu et al., 2015), baseflow correlation (Stedinger and Thomas, 1985; Zhang and Kroll, 2007b), drainage area ratio (Hirsch, 1979), and climate adjustment method (Laaha and Blöschl, 2005). These methods considered three groups of information in terms of choosing a reference gage: spatial distance, basin characteristics, and streamflow correlation (Laaha and Blöschl, 2005). The spatial distance methods include: (1) the use of spatially contiguous hydrologic regions which developed hydrologic homogenous regions and selected the reference gage from the same hydrologic regions where the ungaged site was located (Laaha and Blöschl, 2006); (2) spatial proximity which selected the nearest gage as the reference gage (Archfield and Vogel, 2010; Stedinger, 1993); and (3) the use of a nested gage which employed the immediate downstream or upstream gage as the reference gage (Laaha and Blöschl, 2005). The basin characteristics methods measured similarity between the drainage areas of the potential reference gages and ungaged sites using climatic, land use/land cover, soil, morphologic and geologic characteristics and chose the most similar gage as the reference gage (Merz and Blöschl, 2004; Nathan and McMahon, 1990). The streamflow correlation method required short-term streamflow records or nominal measurements of streamflow at the ungaged site to select a reference gage. When streamflow correlation could be reliably established, the gage with the highest correlation will be used as the reference gage (Robson and Reed, 1999; Stedinger and Thomas, 1985; Yuan, 2013; Zhang and Kroll, 2007b).

Reference gages have been widely used by federal, state, and local resources agencies for water resources management and conservation purposes, including water allocation, flood control, drought management, ecosystem flow need studies, and sediments and nutrients management (Yuan, 2013; Zhang and Kroll, 2007a). The selection of reference gages has a profound impact on management strategy formulation and enforcement. While there is no streamflow measurements at the ungaged site for water resources managers to employ the aforementioned methods, Archfield and Vogel (2010) proposed a geostatistical procedure, the map correlation method, which estimated streamflow correlation with spatial models between potential reference gages and ungaged sites without the prerequisite of having streamflow records at the ungaged sites, and selected a reference gage with the highest correlation. In real management practices, the reference gage was often selected based on professional judgment or expert opinions considering spatial distance, basin characteristics, and streamflow correlation if available, which was described by Patil and Stieglitz (2012). For instance, the Susquehanna River Basin Commission (SRBC) has developed a comprehensive check list which compares drainage area, spatial distance, climatic, land use/land cover, soil, depth to rock, geologic, and glacial activity, etc., to assist hydrologists to determine reference gages for low flow protection management.

How to best select reference gages and assess various selection methods have been extensively investigated and documented in literature in which jackknife simulations or bootstrap resampling were typically involved using long-term gages as hypothetical ungaged sites (Archfield and Vogel, 2010; Laaha and Blöschl, 2005). These rigorous cross validation approaches are valuable for assessing reference gage selections when long-term streamflow records are available for both "ungaged" and reference gage sites. Interestingly, a conundrum faced in water resources management is whether the selected reference gage is adequate for estimating streamflow at the ungaged site to satisfy specific management objectives, and how to proceed if it is not. Hydrologists do not have long-term continuous streamflow records at the ungaged site and thus could not use bootstrap resampling to evaluate the selected reference gages. The ultimate criteria to assess the reference gage are then to compare estimated with observed streamflow statistics. However, there are no observed streamflow statistics unless taking years and financing resources to set up a gage and obtaining streamflow records at the ungaged site is possible. Furthermore, when adequate streamflow records are obtained, a reference gage will no longer be needed.

Unlike previous studies focusing on evaluating reference gage selection methods based on hypothetical ungaged sites, this study seeks the answer of whether a used reference gage in practice is appropriate for streamflow estimation at the ungaged site and how to choose a better reference gage if it is not. Originating from real management scenarios, this study contributes a step-by-step method to allow hydrologists to obtain effective flow measurements with an optimized budget, evaluate performances of used reference gages, and identify appropriate alternative reference gages if undesirable. Presented in the following sections are the methodology and results of reference gages assessment. Based on the assessment results, the advantages and limitations of the method will be discussed as well.

2. Material and methods

The proposed method to assess used reference gages includes three steps: (1) a field campaign protocol is introduced to collect onsite instantaneous flow measurements; (2) streamflow correlation analysis and streamflow ratio analysis is performed to comprehensively assess the reference gage; (3) upon outcomes of correlation analysis and streamflow ratio analysis, map correlation method is employed to identify additional suitable gages, if the original reference gage is not desirable. To test the proposed method, it was applied to assess 18 reference gages used by SRBC to manage water withdrawals with passby flow requirements. The proposed approach was aimed at conducting a posterior assessment of reference gages selected using various methods including map correlation and spatial proximity. To assess reference gage selection methods themselves, jack-knife cross validation techniques are often used.

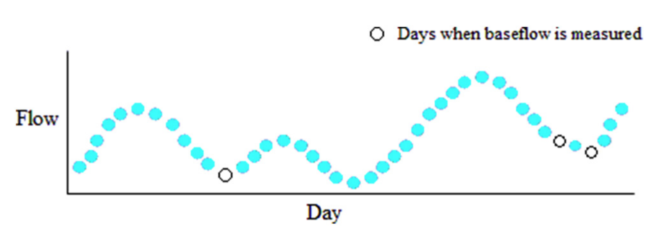

Fig. 1. Schematic of desirable single and paired baseflow measurements.