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

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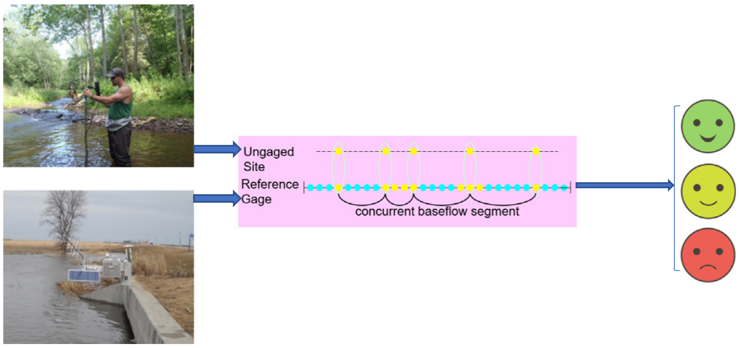
HIGHLIGHTS

- 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.

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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.

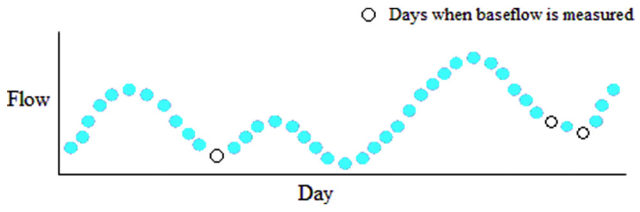

Fig. 1. Schematic of desirable single and paired baseflow measurements.

2.1. Field campaign protocol

The pressing need of evaluating a used reference gage is to obtain onsite streamflow measurements at the ungaged site. Operation and maintenance of a streamflow gage will continuously involve cost of administrative, building, and utility construction and data management (Norris et al., 2008) and extensive field and office labor, which certainly cannot be achieved for most ungaged streams. Instead of managing a streamflow gage, a sound protocol is warranted to guide the collection of efficient and effective onsite streamflow measurements to estimate streamflow correlation. Based on the impact of instantaneous streamflow measurements on low streamflow statistics estimation and hydrologic modeling derived from a range of studies, the field campaign protocol is developed as the first step in this study as follows (Eng and Milly, 2007; Riggs, 1972; Seibert and Beven, 2009; Stedinger and Thomas, 1985; Zhang and Kroll, 2007a). It should be noted that this approach and field campaign protocol is aimed at assessing reference gages used for water supply, drought, and low flow management purposes. The streamflow data obtained during baseflow conditions is not relevant for assessing reference gages for flood risk management applications.

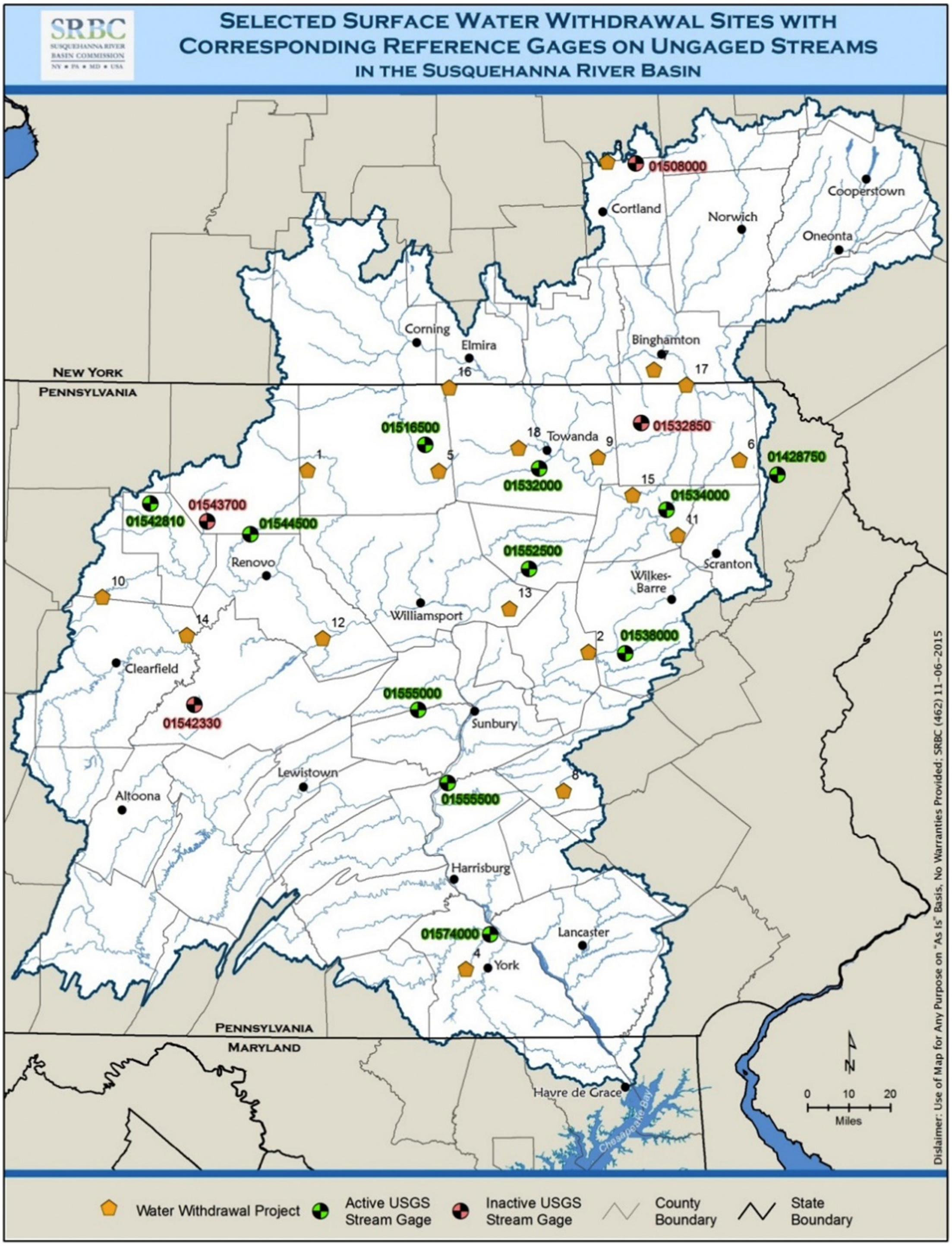

Fig. 2. The reference gages and ungaged water withdrawal sites used in the study.

1. The streamflow measurements should be obtained during the low flow months, which is the period of July through November in the study area.
2. Generally, 10 streamflow measurements during baseflow conditions are needed. Based on the work of Stedinger and Thomas (1985), Zhang and Kroll (2007a) and others, 10 or more streamflow measurements are often considered to be sufficient for baseflow correlation. Considering the effort and cost to obtain field streamflow measurements, 10 streamflow measurements per site were used in this study. Among these, six single measurements should be obtained on different recessions. Additionally, two pairs of measurements should be obtained and each pair of measurements should be obtained on the same recession. Fig. 1 shows the schematic of a single measurement and a pair of measurements.

3. Ideally, streamflow measurements should be obtained as far as possible from rainfall events that happened in the watershed that drains to the monitoring location (Fig. 1). For single measurements taken on individual recessions, the measurement should be obtained after at least five days of dry weather. For a pair of measurements taken on the same recession, the first measurement should be obtained three or more days after a rainfall event and should allow for two days of dry weather between the measurements. The daily spacing of relevant streamflow measurements was used according to the findings of Reilly and Kroll (2003) and Zhang and Kroll (2007a).
4. Ideally, to minimize the diurnal fluctuation, the streamflow measurements should be obtained on a cloudy day if field schedule allows.
5. At most, 4–6 measurements in a single year shall be obtained unless the streamflow in that given year was extremely low, such as the 7-day-10-year low flow condition. This means it requires two years or more time to get all the measurements needed for assessing the reference gage.

To collect streamflow measurements according to the field campaign protocol, hydrologic conditions at the reference gage and weather forecast for the ungaged site are monitored to ensure criteria are met to conduct streamflow measurement at the ungaged site.

2.2. Streamflow correlation analysis and streamflow ratio analysis

Correlation analysis is used as the second step in this study to explore the correlation between the instantaneous streamflow measurements obtained from the ungaged site and the concurrent streamflow for the reference gage. To minimize the impact of comparing daily streamflow data and instantaneous streamflow measurements, the nearest 15-minute streamflow value for each reference gage was used in the analysis. Without observed streamflow statistics and an imminent plan for setting up a gage, streamflow correlation between an ungaged site and a reference gage is the most straightforward indicator of demonstrating how well the hydrology in the reference gage could represent the hydrology in the ungaged site.

Correlation analysis, one of the most commonly used statistics, is used to quantify the degree of flow correlation between reference gages and ungaged sites. When a sample of data is obtained, the sample correlation coefficient is estimated via correlation analysis. While there are multiple correlation coefficients, the Pearson product-moment correlation coefficient, denoted by ρ, is the one mostly used.

$$\rho = \frac{\mathrm{cov}(Q_g, Q_u)}{\sigma_g \sigma_u} \tag{1}$$

where Q_g is the streamflow at the reference gage; Q_u is the streamflow at the ungaged site; σ_g is the standard deviation of streamflow at the reference gage; and σ_u is the standard deviation of streamflow at the ungaged site. ρ ranges between −1 and +1 and quantifies the direction and strength of linear correlation between the two variables. The sign of ρ indicates the direction of association, and the magnitude of ρ measures the strength of association. A correlation coefficient of 0 shows no linear association between the two variables. It is noted that 10 streamflow measurements may be insufficient to calculate reliable Pearson correlation coefficients. Therefore, rank-based correlation coefficients, including Spearman's ρ and Kendall's τ, were also explored. High streamflow correlations indicate that the hydrologic conditions in the reference gage may closely resemble the hydrologic conditions in the ungaged site and thus, the reference gage used for regulatory purposes may be appropriate. Low streamflow correlations denote that the used reference gage may be inappropriate. It is noted that the number of data points is not ideal for calculating reliable correlation coefficients, which is due in part to the effort and cost associated with obtaining

Table 1
Water withdrawal sites with passby flow requirements and corresponding reference gages.

Withdrawal site	Water source	Ungaged site drainage area (mile^2)	Passby flow (cfs)	Reference gage no.	Reference gage name	Reference gage drainage area (mile^2)
1	Elk Run	11.7	5.15	01542810	Waldy Run near Emporium, PA	5.24
2	East Branch Briar Creek	8.0	0.63	01538000	Wapwallopen Creek near Wapwallopen, PA	43.8
3	Unnamed Tributary to Crooked Lake	1.0	0.44	01508000	Shackham Brook near Truxton, NY	3.16
4	Little Conewago Creek	21.2	4.96	01574000	West Conewago Creek near Manchester, PA	510
5	Fellows Creek	5.2	0.79	01516500	Corey Creek near Mainesburg, PA	12.2
6	East Branch Tunkhannock Creek	2.0	0.70	01534000	Tunkhannock Creek near Tunkhannock, PA	383
7	Unnamed Tributary to West Fork of Little Snake Creek	0.3	0.11	01532850	Middle Branch Wyalusing Creek near Birchardville, PA	5.67
8	Headwaters of Unnamed Tributary to Swatara Creek	0.1	0.03	01555500	East Mahantango Creek near Dalmatia, PA	162
9	Wyalusing Creek	194.8	55.02	01534000	Tunkhannock Creek near Tunkhannock, PA	383
10	Bennett Branch	57.4	14.06	01543700	First Fork Sinnemahoning Creek at Wharton, PA	182
11	Buttermilk Creek	23.6	6.48	01428750	West Branch Lackawaxen River near Aldenville, PA	40.6
12	Fishing Creek	181.4	66.14	01555000	Penns Creek at Penns Creek, PA	301
13	Little Muncy Creek	41.3	16.60	01552500	Muncy Creek near Sonestown, PA	23.8
14	Mosquito Creek	70.5	29.16	01544500	Kettle Creek at Cross Fork, PA	136
15	Meshoppen Creek	114	32.28	01534000	Tunkhannock Creek near Tunkhannock, PA	383
16	Seeley Creek	26.6	5.41	01516500	Corey Creek near Mainesburg, PA	12.2
17	Snake Creek	73.4	22.40	01534000	Tunkhannock Creek near Tunkhannock, PA	383
18	Sugar Creek	151	31.74	01532000	Towanda Creek near Monroeton, PA	215

instantaneous streamflow measurements. Whenever adequate financial resources are available, it is encouraged to obtain and use additional streamflow measurements to assess reference gage performance.

In addition to correlation analysis, the streamflow ratio and drainage area ratio methods were also compared in assessing reference gages. When a reference gage is used, a common assumption is that streamflow per unit area for a site of interest is the same as that for the reference gage. Based on this assumption, drainage area ratio method is used to estimate streamflow at the site of interest as follow

$$Q_u = \frac{A_u}{A_g} Q_g \tag{2}$$

where A_u is the drainage area for the ungaged site and A_g is the drainage area for the reference gage. Therefore, for an ideal reference gage, the drainage area ratio is equal to the streamflow ratio without considering measurement error. When multiple streamflow measurements are obtained, the average of the multiple streamflow ratios is employed. The error between drainage area ratio and streamflow ratio can be used to evaluate a reference gage, which is calculated as follows:

$$\varepsilon = \frac{A_u}{A_g} - \frac{Q_u}{Q_g} \tag{3}$$

To comprehensively assess the error, the relative error is employed as well, which is calculated as follows:

$$RE = \frac{\varepsilon}{\frac{Q_u}{Q_g}} \tag{4}$$

2.3. Map correlation method and BaSE tool

The final step is to provide a feasible, post-examination solution for water resources managers when used reference gages exhibit poor correlations with ungaged sites. An alternative method is recommended and explored to identify additional a suitable reference gage.

The map correlation method proposed by Archfield and Vogel (2010) is employed in this study in consideration of geography and applicability. Based on geostatistics, the map correlation method is comprised of two major assumptions: (1) it was possible to estimate the streamflow correlation between the daily streamflows at a gage and an ungaged site for any location in the study area; and (2) Pearson correlation coefficient values were isotropic across the study area. The first assumption was derived from the conceptual model described by Woods and Sivapalan (1999), which assumed that runoff exists at any location. Pearson correlation coefficient values were estimated from the logarithms of daily streamflow values. By virtue of these assumptions, the variogram model could be established and ordinary kriging was used to estimate the unbiased value of Pearson correlation coefficient between any ungaged sites and the reference gage. Ordinary kriging uses weighted average of the observations to estimate the statistics at unsampled sites (Isaaks and Srivastava, 1989) as

$$x_u = \sum_{i=1}^{n} w_i x_i \tag{5}$$

where, x_u is the estimate for the unsampled site, w_i is the weight at point i, x_i is the observation at point i, and n is the number of observations.

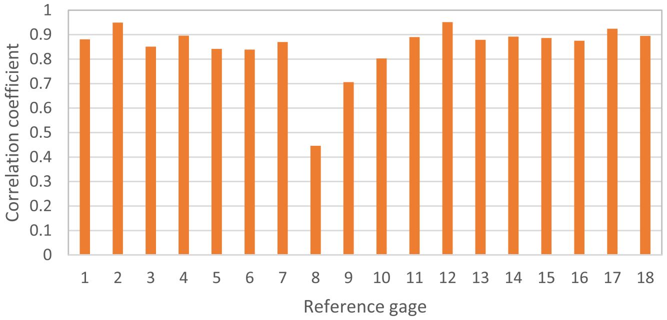

Fig. 3. Flow correlation analysis results for the 18 reference gages used in the study.

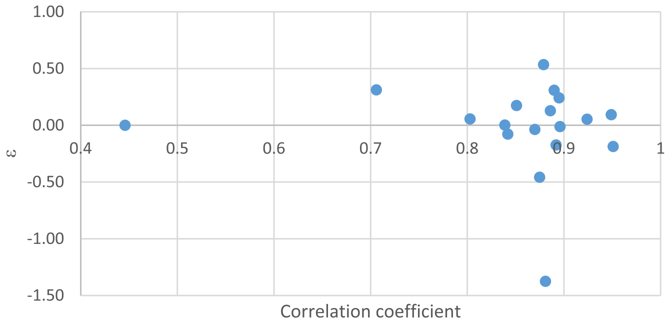

Fig. 4. The error of drainage area ratio vs streamflow ratio for the 18 reference gages.

The map correlation method provided a novel approach to directly estimate streamflow correlation when there were no streamflow records for the ungaged site. The Baseline Streamflow Estimator (BaSE) is an ease-of-use tool to implement the map correlation method for Pennsylvanian streams and rivers. BaSE was developed by the U.S. Geological Survey (USGS) in cooperation with the Pennsylvania Department of Environmental Protection (PADEP), SRBC, and The Nature Conservancy (TNC), to estimate baseline streamflow at a daily scale for ungaged streams in Pennsylvania (Stuckey et al., 2012).

In this step, the gages recommended by BaSE were evaluated using the streamflow correlation analysis and streamflow ratio analysis. The results were compared with those of the original reference gages with respect to streamflow correlation, error, and relative error simultaneously.

2.4. Study area and reference gages evaluated

The Susquehanna River is the largest river lying entirely in the United States that drains into the Atlantic Ocean, which constitutes more than 49,000 miles of waterways and drains 27,500 mile^2. It originates from Otsego Lake at Cooperstown, NY, and continues southward into Pennsylvania and is joined by the Chemung River at Athens, PA, the West Branch Susquehanna River at Sunbury, PA, and the Juniata River at Newport, PA. After that, the Susquehanna River becomes an impressive river nearly a mile wide with a series of hydroelectric power facilities. The Susquehanna River Basin comprises 43% of the Chesapeake

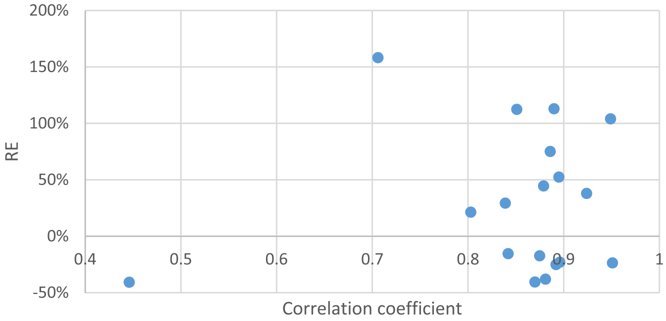

Fig. 5. The relative error (RE) of the drainage area ratio vs streamflow ratio for the 18 reference gages.

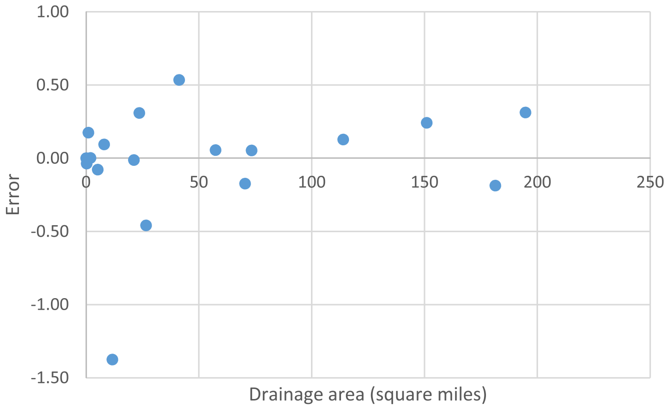

Fig. 6. The error of drainage area ratio vs streamflow ratio with respect to the drainage area of the ungaged site for the 18 reference gages.

Bay's drainage area and provides nearly one-half of the freshwater flow to the Bay at Havre De Grace (SRBC, 2013; Zhang et al., 2016).

The Susquehanna River Basin is covered by three major physiographic provinces, Appalachian Plateau, Valley and Ridge, and Piedmont, and over half are forested lands. The basin provides an ample source for water use, including power generation, public water supply, manufacturing, mining, irrigation, recreation etc. In practice, water use or water resources projects are often located in ungaged sites where a historical record of streamflow measurements is not available. Thus, reference gages are widely used for estimating streamflow statistics in ungaged sites.

Overall, SRBC uses hundreds of reference gages for water resources conservation, control, utilization, and management purposes. In this study, 18 reference gages were identified as a representative sample to test the proposed approach. It is noteworthy that the proposed approach is based on field campaign to obtain instantaneous flow measurements and it is not feasible to test the approach with all the reference gages. The SRBC's water withdrawal project database was used in conjunction with Geographic Information System (GIS) software to select the 18 reference gages. A GIS shapefile with query results was generated for screening to ensure adequate representation of a variety of characteristics, including water use sectors, geographic distributions, hydrologic features, and watershed characteristics. The drainage area of sampled ungaged sites varied from 0.1 mile^2 to 194.8 mile^2, which covered from headwaters to tributary watersheds. Fig. 2 shows the spatial locations of 18 ungaged sites and corresponding reference gages. Table 1 summarizes site information of water source, drainage area, and passby flow with reference gage.

3. Results and discussion

According to the field campaign protocol, 10 onsite instantaneous streamflow measurements were obtained at each ungaged site during a 4-year period from 2011 to 2014. Concurrent streamflow records at each corresponding reference gage were retrieved from the USGS National Water Information System (NWIS) network.

3.1. Field campaign protocol

Compared to setting up a streamflow gage, the field campaign protocol shows advantages in feasibility and applicability. The average annual cost to operate and maintain a streamflow gage in 2008 was $14,100 (Norris et al., 2008) and multiple years of efforts and budgets will be needed for maintaining a streamflow gage. In contrast, the field protocol could provide flow measurements to evaluate reliability of reference gages with much less cost. This approach is particularly meaningful for headwater streams where instream habitat and ecosystems are vulnerable yet unpromising to set up a streamflow gage.

As the protocol was implemented in the field, several observations have been made. Reference gages used in the study were to determine passby flows for low flow protection; thereof the temporal window for collecting discharge measurements was targeted on dry months of July through November in the Mid-Atlantic region. The schedule need to be adjusted based on meteorological characteristics, geographic regions, and regulatory purposes (i.e., flood monitoring). It is noted that the accuracy of weather forecasts had a significant impact on arranging staff for field work, especially for widespread sites in large basins. Flexibility of field arrangement shall be considered and close watch of flow conditions at reference gages is needed. After several discharge measurements were gained, a preliminary data screening is needed to make sure the data are widely distributed. Clustered data points have minimal benefits in correlation analysis with wasted labor and efforts. The Surface Water and Ocean Topography (SWOT) satellite, which will be launched in 2021, will provide water flux observations for rivers of at least 50-meter wide and may provide useful data for assess appropriateness of reference gages in the future (Biancamaria et al., 2016).

3.2. Correlation analysis and streamflow ratio analysis

Correlation analysis was conducted between discharge measurements at ungaged sites and concurrent streamflow records at corresponding reference gages. The resulting Pearson correlation coefficients of 18 reference gages were shown in Fig. 3. The rank-based correlation (Spearman ρ and Kendall's τ) results share a very similar pattern with the Pearson correlation coefficients, thus the results are not repeated here. In general, flow measurements at withdrawal sites were highly correlated with reference gage streamflow records. The correlation coefficients were greater than 0.9 for 3 reference gages and greater than 0.8 for 16 sites. Only one reference gage has correlation coefficient of less than 0.7.

A poor flow correlation was noted for site 8. Site 8 was located in the headwaters of Swatara Creek. The corresponding reference gage was USGS 01555500. The drainage areas of site 8 and its reference gage were 0.1 mile^2 and 162 mile^2, respectively. The reference gage was

Table 2
Reference gages, BaSE-recommended gages, and associated performance metrics.

Site	BaSE-recommended gage or reference gage	Streamflow correlation	DA (mile^2)	Error	Relative error
1	01548500 Pine Creek at Cedar Run, PA	0.93	604	−0.0008	−4%
	01549700 Pine Creek below Little Pine Creek near Waterville, PA	0.92	944	−0.0008	−6%
	01544500 Kettle Creek at Cross Fork, PA	0.94	136	−0.0067	−7%
	01545600 Young Womans Creek near Renovo, PA	0.82	46.2	−0.1768	−41%
	01520000 Cowanesque River near Lawrenceville, PA	0.94	298	−0.0339	−46%
	Reference gage 01542810	0.88	5.2	−1.38	−38%
8	01472000 Schuylkill River at Pottstown, PA	0.61	1147	0.00001	14%
	01468500 Schuylkill River at Landingville, PA	0.56	133	0.00031	69%
	01470500 Schuylkill River at Berne, PA	0.56	355	0.00007	33%
	01471000 Tulpehocken Creek near Reading, PA	0.61	211	0.00005	13%
	Reference gage 01555500	0.45	162	−0.00041	−41%

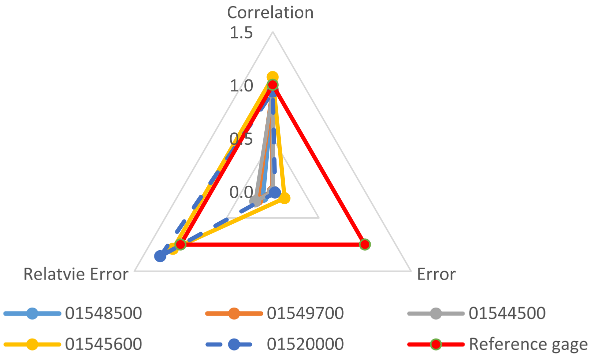

Fig. 7. The radar chart of correlation, relative error, and error of the BaSE-recommended gages and the original reference gage for site 1, normalized by corresponding metric of the reference gage.

chosen primarily because of spatial proximity. Poor flow correlation suggests that the reference did not predict low flow conditions with sufficient accuracy. Site 8 is in a small spring setting while the reference gage is on a much larger stream. Springs are in unique hydrogeologic settings, which often occur in steeply sloping terrains. The outflow rates will depend upon the fracture size and importance of lateral drainage (Dingman, 2015; Smakhtin, 2001). The discrepancies between site 8 and the reference gage in drainage area, groundwater discharge direction, magnitude, and timing were likely to be the primary causes of the poor flow correlation.

The error of drainage area ratio is shown in Fig. 4 and the relative error is shown in Fig. 5. The average error − 0.02 with minimum of −1.38 and maximum of 0.53. One interesting observation is that the difference is not highly correlated with streamflow correlation coefficients. Interestingly, for site 8 with low correlation coefficient value, the difference between drainage area ratio and streamflow ratio is only −0.04. On the other hand, for site 1, the correlation coefficient is 0.88 but the difference between drainage area ratio and streamflow ratio is −1.38. The average relative error is 29% with minimum of −41% and 158%. From Fig. 5, it can be seen that the relative error is not highly correlated with streamflow correlation either. This demonstrates the need for streamflow ratio analysis in addition to streamflow correlation analysis. A reference gage is deemed as appropriate when it has high streamflow correlation, low error and relative error. The reference gage used for site 1 has error of −1.38; the reference gage for site 8 has a streamflow correlation of 0.45; and the reference gage for site 9 has the relative error of 158%. Therefore, these three reference gages are not preferred and map correlation method is conducted to identify additional gages.

Reilly and Kroll (2003) and Zhang and Kroll (2007a) concluded that a correlation coefficient of 0.6 or higher is needed for baseflow correlation analysis. The results of this study provide a closer look at baseflow correlation. While it is expected that a higher correlation between stream gage records and instantaneous streamflow measurements will improve the appropriateness of a reference gage, consideration of the resulting error associated with using the reference gage is warranted.

Fig. 8. The radar chart of correlation, relative error, and error of the BaSE-recommended gages and the original reference gage for site 8, normalized by corresponding metric of the reference gage.

To explore how drainage area impacts the error associated with the drainage area ratio vs streamflow ratio methods, the errors are graphically shown in Fig. 6. While a clear relationship between error and drainage area is not observed, the error does show higher variability for sites with smaller drainage areas (less than 50 mile^2). When an appropriate reference gage is used for an ungaged site with a small drainage area, the error could be minimal. However, when an inappropriate reference gage is used, the error could be significantly larger. This demonstrates that the appropriateness of a reference gage plays a larger role than drainage area itself. In water management practice, though, it is often more difficult to find a reliable and appropriate reference gage for ungaged sites with small drainage areas.

3.3. Map correlation analysis

The map correlation analysis, which is implemented in the BaSE tool, generated up to five reference gages with high correlation coefficients for each ungaged site. The BaSE tool is employed to generate potential reference gages for sites 1, 8, and 9 with inappropriate reference gages identified in the previous section.

The streamflow correlation analyses between onsite flow measurements and concurrent streamflow records of BaSE-recommended reference gages were performed to assess the BaSE-recommended reference gages. For site 9, the used reference gage is also recommended by BaSE tool which indicates that it is the best available reference gage for the ungaged site though it is still not preferred for estimating streamflow at the ungaged site. The results of streamflow correlation analysis and streamflow ratio analysis for sites 1 and 8 are summarized in Table 2, and Figs. 7 and 8.

In Figs. 7 and 8, the streamflow correlations, relative errors, and errors are normalized by the original reference gage. The points closer to the origin (0,0,0) have better performance. BaSE-recommended gages for site 1 exhibited high correlations with onsite discharge measurements. Furthermore, the errors and relative errors for 3 gages (01548500, 01549700, and 01544500) are much less than those of the original reference gage. From Fig. 6, it can be seen that these three BaSE-recommended gages appear to better represent the hydrologic conditions in the ungaged site. Note that the drainage areas of BaSE-recommended reference gages are generally much greater than drainage areas of ungaged sites. The drainage areas of three BaSE-recommended reference gages ranged from 10 to 80 times larger than size of Site 1, which was 11.7 mile^2.

From Fig. 8, it can be seen that two of the BaSE-recommended gages (01472000 and 0147100) have a bit higher streamflow correlation but much less error or relative error. By streamflow correlation, no gages have high streamflow correlation with the ungaged site which is expected as site 8 has a unique hydrogeologic setting and extremely small drainage area. This indicates a preferred reference gage may not exist for an extremely small watershed or unique hydrogeologic setting and onsite monitoring may be warranted.

For other sites, 10 of 15 original reference gages selected by SRBC are included in the list of BaSE-selected gages. It is noted that BaSE tool is only available for limited regions. Experts provide knowledge of local hydrology and water development which could be used to refine map correlation selections. The map correlation method could be used to provide a list of candidate reference gages, especially when BaSE or related tools are available to streamline implementation of the map correlation approach.

4. Conclusions

Selection of appropriate reference gages for performing hydrologic analyses at ungaged sites is critical in water resources management practices. This study proposed an effective method to posteriorly examine the performance of selected reference gages, comprising a field campaign protocol, correlation analysis and streamflow ratio analysis, and map correlation. The method has been tested with 18 reference gages in the Susquehanna River Basin used for low flow protection purposes.

The field campaign protocol made it affordable and manageable to obtain effective onsite discharge measurements at ungaged sites. The subsequent streamflow correlation analysis and streamflow ratio analysis provide criteria to assess reference gages. The map correlation method generates alternative reference gages when the selected reference gage is undesirable. It should be noted that since it is difficult to find an appropriate reference gage for an ungaged site possessing an extremely small drainage area and unique hydrogeologic settings, an appropriate reference gage may not exist, and on-site monitoring may be warranted.

Unlike previous hydrologic studies used for hypothetical ungaged streams, the posterior assessment method was based on water management practices where no continuous streamflow records were available for validation. It provides a valuable tool for water resources managers and hydrologists to posteriorly assess reference gages with feasible cost and improved confidence in meeting regulatory objectives.

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