# Evaluation of Reference Gages for Passby Flow Determinations and Monitoring in the Susquehanna River Basin

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Susquehanna River Basin Commission

The Susquehanna River Basin Commission was created as an independent agency by a federal-interstate compact* among the states of Maryland and New York, the Commonwealth of Pennsylvania, and the federal government. In creating the Commission, the Congress and state legislatures formally recognized the water resources of the Susquehanna River Basin as a regional asset vested with local, state, and national interests for which all the parties share responsibility. As the single federal-interstate water resources agency with Basinwide authority, the Commission's goal is to coordinate the planning, conservation, management, utilization, development, and control of Basin water resources among the public and private sectors.

**Statutory Citations: Federal - Pub. L. 91-575, 84 Stat. 1509 (December 1970); Maryland - Natural Resources Sec. 8-301 (Michie 1974); New York - ECL Sec. 21-1301 (McKinney 1973); and Pennsylvania - 32 P.S. 820.1 (Supp. 1976).*

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## GLOSSARY

**Average Daily Flow (ADF)** – The average of mean daily streamflows for a period of record.

***de minimis* Withdrawal** – If the surface water or groundwater withdrawal impact is minimal in comparison to the natural or continuously augmented flow of a stream or river, no passby flow was required. This is referred to as the *de minimis* withdrawal.

**Passby Flow –** A prescribed streamflow threshold at which a regulated withdrawal must cease to limit instream impacts during low flow conditions.

**Percent Exceedance Flow (Px) –** The flow that is exceeded a certain percent of the time. For example, a June 95 percent exceedance (P95) flow represents a low flow that has been exceeded 95 percent of all days in June over the period of record.

**Reference Gages** – Selected USGS stream gages to best represent hydrologic conditions at ungaged sites based on similar watershed characteristics. Reference gages are required to have a minimum of 10 recent years of record and are used to calculate streamflow statistics and determine passby flow thresholds.

**Seven-day, Ten-year (7Q10) Low Flow** – Annual 7-day minimum flow with a 10-year recurrence interval.

**Trigger Gages** – Selected real-time USGS stream gages to best represent hydrologic conditions at ungaged sites based on similar watershed characteristics. Trigger gages are used for low flow monitoring, operations, and compliance.

## EXECUTIVE SUMMARY

In its review of water withdrawal projects, the Susquehanna River Basin Commission (Commission) establishes appropriate limitations, conditions, and mitigation to allow for reasonable water use while minimizing impacts on downstream uses, including instream uses. A passby flow is a prescribed streamflow threshold at which a regulated withdrawal must cease to limit instream impacts during low flow conditions. In many instances, passby flow thresholds associated with regulated withdrawals from ungaged streams are estimated using a United States Geological Survey (USGS) reference gage. In doing so, the reference gage is selected based on hydrologic similarities between the gaged and ungaged watersheds. This study aims to evaluate the predictive accuracy associated with using reference gages to estimate passby flow conditions at ungaged withdrawal sites.

Twenty approved withdrawal projects with passby flow requirements on ungaged streams throughout the Susquehanna River Basin (Basin) were selected for evaluation. Two of these projects were later eliminated due to site access issues. Dictated by local hydrologic conditions, field discharge measurements were collected at 18 ungaged withdrawal sites during baseflow periods. In addition to Commission-selected reference gages, reference gages identified using the USGS Pennsylvania Baseline Streamflow Estimator (BaSE) map correlation method were also evaluated. Correlation analyses were performed on field discharge measurements at ungaged withdrawal sites and concurrent reference gage streamflow data. Overall, the coefficients of determination ($r^2$) between the discharge measurements and gage data were found to be high, ranging from 0.69 to 0.99. An exception was noted for site A10 ($r^2 = 0.37$), located at Sweet Arrow Spring in the headwaters of an unnamed tributary to Swatara Creek. The discrepancies between site A10 and the reference gage, in terms of drainage area and hydrogeologic setting, were deemed to be primary factors contributing to the poor flow correlation.

Annual mean and low flow statistics calculated using USGS StreamStats regression equations were compared with values computed using the reference gage drainage area ratio method. The passby flow thresholds calculated using each method were generally found to be in agreement. The differences in computed average daily flow values were less than 5 cubic feet per second (cfs) for 70 percent of the evaluated withdrawal sites, and the differences in the 7-day, 10-year low flow values were less than 3 cfs for 95 percent of the sites assessed. Monthly percent exceedance flow statistics computed using the reference gage drainage area ratio method were also compared with values calculated using BaSE-generated daily mean flow time series. The average difference between the two sets of passby flow thresholds varied from 0.1 to 28.8 cfs. The results suggest that regression-based applications could serve as comparative tools for informing passby flow determinations when applicable criteria are met.

Selection of appropriate reference gages for performing hydrologic analyses at ungaged withdrawal sites is critical in determining passby flow thresholds and monitoring. This study recommended continued adherence to the Commission’s standard reference gage selection criteria and exercising caution in very small or unique hydrologic/geologic settings to ensure low flow protection objectives are met. When using regression-based applications as comparative tools, the importance of drainage area size, reservoir regulation impacts, and local precipitation patterns cannot be neglected in selecting reference gages for passby flow implementation.

# 1.0 INTRODUCTION

## 1.1 Regulatory Authority

The Susquehanna River Basin Commission (Commission) regulates surface water and groundwater withdrawals, consumptive water uses, and diversions of water subject to 18 CFR Part 806 - Review and Approval of Projects. The specific purposes of the regulations are designed to avoid conflict among water users, protect public health, safety, and welfare, control water quality, consider economic development factors, protect fisheries and aquatic habitat, and safeguard the Chesapeake Bay (18 CFR § 806.2). For groundwater projects initiated on or after July 13, 1978, and surface water projects initiated on or after November 11, 1995, involving a water withdrawal from groundwater or surface water or a combination of such sources of an average of 100,000 gallons per day (gpd) on a consecutive 30-day basis, project sponsors shall submit applications to the Commission and obtain an approval prior to any actions. For consumptive use projects initiated on or after January 23, 1971, involving a consumptive water use of an average of 20,000 gpd or more on a consecutive 30-day basis, project sponsors shall submit applications to the Commission and obtain an approval prior to any actions. For any unconventional natural gas project involving a withdrawal, diversion, or consumptive use, regardless of the quantity, project sponsors shall submit applications to the Commission and obtain an approval prior to any actions (18 CFR § 806.4). To avoid duplication of work and cooperate with other member state agencies, the Commission develops agreements of understanding with agencies of signatory parties regarding joint review of projects. With the standards set forth in 18 CFR § 806.23, the Commission may deny an application, limit, or condition an approval to ensure that the withdrawal will not cause significant adverse impacts to the water resources of the Susquehanna River Basin.

## 1.2 Passby Flow Policy

In its review of water withdrawal projects, the Commission establishes appropriate limitations, conditions, and mitigation to allow for reasonable water use while minimizing impacts on downstream uses, including instream uses. A passby flow is a prescribed streamflow threshold at which a regulated withdrawal must cease to limit instream impacts during low flow conditions. Passby flows may be associated with surface water and groundwater withdrawal approvals under 18 CFR § 806.23. When the natural flow is less than the prescribed passby flow, no water may be withdrawn from the source and the entire natural flow shall be allowed to pass the point of withdrawal.

The Commission's former Policy No. 2003-01, *Guidelines for Using and Determining Passby Flows and Conservation Releases for Surface-Water and Ground-Water Withdrawal Approvals*, was based on a position paper by the Pennsylvania Fish and Boat Commission (PFBC) for use in reviewing water allocation permits. The policy specified that, if the surface water or groundwater withdrawal impact was minimal in comparison to the natural or continuously augmented flow of a stream or river, no passby flow was required. Minimal was defined as 10 percent or less of the natural or continuously augmented 7-day, 10-year low flow (7Q10) of the stream or river. This was referred to as the *de minimis* withdrawal threshold.

For coldwater trout streams with drainage areas less than 100 square miles, located within defined areas of Pennsylvania and Maryland, passby flows were determined based on *Instream Flow Studies, Pennsylvania and Maryland* (Denslinger et al., 1998). The Pennsylvania-Maryland Instream Flow Study (PA-MD IFS) method used delineated hydrologic regions, regional reference gages, an Excel-based withdrawal/passby flow evaluation tool, habitat loss curves, and habitat loss criteria associated with Pennsylvania Chapter 93 Use Designations (Pennsylvania Code) to assign a passby flow as a percentage of average daily flow (ADF).

For proposed withdrawals from streams located in undefined hydrologic regions of the aforementioned study, passby flows were assigned based on a defined percentage of ADF contingent on the Chapter 93 Use Designation for the source stream. The ADF of the stream at the point of withdrawal was estimated by proportioning the calculated ADF from an acceptable USGS reference gage based on the drainage area ratio. Other considerations in the passby flow determination process included published species and habitat information, consultation with state fishery management agencies, and completion of site specific instream flow studies. In no case was the passby flow to be less than 7Q10. Former Policy 2003-01 passby flow determination specifications are presented in Table 1.

***Table 1. Former Policy 2003-01 Passby Flow Determination Specifications***

| **Drainage Area ($mi^2$)** | **Region** | ***de minimis* Withdrawal** | **Chapter 93 Use Designation** | **Habitat Loss** | **Passby Flow** |
|---|---|---|---|---|---|
| </= 100 | Hydrologic Regions in PA-MD IFS | 10% of 7Q10 | Exceptional Value (EV) | <5% | Percent of ADF or 7Q10, whichever is greater |
| | | | High Quality (HQ) | <5% or <7.5%* | |
| | | | Coldwater Fishery (CWF) – Class B Wild Trout Stream | <10% | |
| | | | Coldwater Fishery (CWF) – Class C or D Wild Trout Stream | <15% | |
| > 0 | Remainder of Basin | | EV, HQ, & streams with naturally reproducing trout | N/A | 25% of ADF |
| | | | Trout Stocking Fishery (TSF) & Warm Water Fishery (WWF) | | 20% of ADF |
| | | | Streams impaired by acid mine drainage | | 15% of ADF |
| | | | Other Streams | | 7Q10 |

* A habitat loss of 7.5% may be allowed if certain conditions are met.

The Commission's former Policy 2003-01 was replaced by a new Low Flow Protection Policy (LFPP), adopted in 2012, to integrate The Nature Conservancy's (TNC) *Ecosystem Flow Recommendations for the Susquehanna River Basin* (DePhilip and Moberg, 2010) and related contemporary instream flow science. The flow recommendations were developed by TNC to protect the Basin's species and natural communities that are sensitive to flow alteration. Considering the naturally-occurring, inter-annual variability of streamflow and ecosystem flow needs, seasonal flow recommendations were determined to be preferable to annual-based flow recommendations (DePhilip and Moberg, 2010). In the LFPP, source streams are classified into six Aquatic Resource Classes (ARC) based on drainage area size. Monthly percent exceedance flow (Px) statistics, which replace the annual low and mean flow statistics 7Q10 and ADF, are used to designate *de minimis* withdrawal and passby flow thresholds.

The LFPP passby flow determination process considers multiple factors including ARC, environmental screenings, hydrologic analyses, habitat loss criteria, *de minimis* withdrawals, withdrawal limits, and special cases to inform low flow protection requirements. The *de minimis* withdrawal thresholds are assessed both individually and cumulatively to determine if, and for which months, passby flow requirements may be imposed. USGS stream gage records are used to calculate passby flow thresholds for gaged sources, while a representative reference gage is selected and utilized to estimate passby flows at ungaged sites using the drainage area ratio method. For sensitive reproducing trout populations in non-glaciated drainage areas less than 100 square miles, the PA-MD IFS method can be used comparatively to determine instream flow protection levels. Table 1 shows the ARCs, descriptions, drainage areas, *de minimis* withdrawals, and typical passby flow thresholds associated with the LFPP.

***Table 2. Low Flow Protection Policy Aquatic Resource Class, de minimis Withdrawal, and Passby Flow Criteria***

| ARC | Description | Drainage Area ($mi^2$) | Monthly *De minimis* Withdrawal | Monthly Passby Flow |
|---|---|---|---|---|
| 1 | Headwaters | <=10 | none | P70 |
| 2 | Creeks | >10 <50 | 5% of P95 | P75 |
| 3 | Small Rivers | >=50 <200 | 5% of P95 | P80 |
| 4 | Medium Tributary Rivers | >=200 <1,000 | 5% of P95 | P85 |
| 5 | Medium Mainstream Rivers | >=1,000 <5,000 | 10% of P95 | P90 |
| 6 | Large Rivers | >=5,000 | 10% of P95 | P95 |

# 2.0 PREDICTIONS IN UNGAGED BASINS

## 2.1 Approaches and Tools

In many instances, water withdrawal projects are located on ungaged streams where a historical record of streamflow measurements is not available. Efforts have been made by regional, national, and international communities to achieve advances in ungaged flow estimation by means of regional regression (Thomas and Benson, 1970; Bingham, 1986; Vogel et al., 1999; Sanborn and Bledsoe, 2006), rainfall-runoff models (Liu and Gupta, 2007; Wagener and Montanari, 2011), baseflow correlation (Hirsch, 1982; Stedinger and Thomas Jr., 1985; Reilly and Kroll, 2003; Zhang and Kroll, 2007), and the drainage area ratio method (Hirsch, 1979; Emerson et al., 2005). The Massachusetts Department of Environmental Protection (MassDEP), in cooperation with USGS, developed the Massachusetts Sustainable-Yield-Estimator (MASYE) tool for estimating unregulated daily mean streamflow, adjusting streamflow for withdrawals, and quantifying the sustainable yield of a basin (Archfield et al., 2010). A concerted effort was made by USGS, the Pennsylvania Department of Environmental Protection (PADEP), TNC, and the Commission in developing the Pennsylvania Baseline Streamflow Estimator (BaSE) to connect daily mean streamflow at ungaged locations with long-term USGS gage records (Stuckey et al., 2012). USGS released a web-based Geographic

Information System (GIS) application, StreamStats, to provide users with access to an assortment of analytical tools for performing hydrologic investigations in gaged and ungaged settings (USGS, 2012). Globally, the International Association of Hydrological Sciences (IAHS) launched an initiative referred to as the IAHS Decade on Predictions in Ungaged Basins (PUB), focused on demonstration data values, estimation of predictive uncertainty, and provision of needed information (Sivapalan, 2003).

Because of the spatial and temporal heterogeneity of land use, vegetation, soil texture, precipitation, etc., it is challenging to predict watershed responses based on limited or no measurements (Sivapalan, 2003). Flow estimation is usually predicated on the selection of a reference gage (also called base station or index gage) under the premise of having similar streamflow responses in watersheds with similar topographic, climatologic, and geologic characteristics. Hirsch (1979) relied on the nearest base station with a long-term, continuous streamflow record to directly reconstruct absent flow measurements or statistics. Patil and Stieglitz (2012) further examined the suitability of selecting a reference gage based on spatial proximity and identified that the predictability of watersheds along the Appalachian Mountains in the Eastern United States was high. Fry et al. (2013) claimed that the drainage area ratio method performed reasonably well when using nearby gage combinations. Smakhtin (1999) applied non-linear spatial interpolation techniques to multiple gaging stations and established flow duration curves (FDCs) for ungaged sites. More recently, Shu and Ouarda (2012) pointed out that multiple geographical distance weighted sources will generate better performance of FDCs at ungaged watersheds than single reference sites. Archfield and Vogel (2010) argued that the nearest reference streamgage was not always a consistent and sensible option, and proposed the map correlation method to choose the most correlated gage for streamflow estimation. Baseflow and daily flow correlations were employed in selecting an index gage where a high flow correlation was detected between ungaged and gaged sites during low flow conditions (Stedinger and Thomas Jr., 1985; Reilly and Kroll, 2003; Zhang and Kroll, 2007; Yuan, 2013). The approach required a nominal number of baseflow/daily flow measurements at a site of interest and an active gage, on the same days.

### 2.2 Reference Gage Selection

As described above, selecting a reliable reference gage remains a key challenge for hydrologists, and there is no standard guidance regarding selection criteria. Ries and Friesz (2000) indicated the drainage area ratio method is generally as accurate as, or more accurate than, regression estimates when the drainage area ratio for an ungaged site is between 0.3 and 1.5. The range could either be reduced or expanded based on practical analyses in different areas (Hortness, 2006). Mohamoud (2008) reconstructed FDCs and streamflow time series in the Mid-Atlantic Region using the drainage area ratio method, which closely matched observed values and strongly recommended selecting the nearest gage to the ungaged site of interest. Patil and Stieglitz (2012) suggested a combination of spatial proximity, climate variability, and geologic setting should be thoroughly considered when transferring flow information from gaged to ungaged sites. While watersheds with similar topography, geology, and physiography, as well as similar baseflow recession characteristics, do not guarantee identical unit runoff, these factors should be considered regarding their dominant influence on baseflow (Stedinger and Thomas Jr., 1985; Eng and Milly, 2007).

Professional judgment and regional knowledge are typically needed in selecting an appropriate reference gage for use in estimating flow statistics for ungaged streams in the Basin. The selection process identifies gages that best represent hydrologic conditions based on similar watershed characteristics, including drainage area, precipitation, topography, geology, and land use, and ideally are located on the same or on a nearby stream, when possible. Reference gages used to determine low flow statistics at a project site should generally be unregulated, of a similar drainage area size compared to the project site, ideally within the one-third to threefold range, and are typically required to have a minimum of 10 recent years of record, representing wet, normal, and dry periods sufficiently. In addition, regional regression-based tools and equations are employed to provide estimated flow statistics for ungaged streams with unique watershed characteristics or located within gaps in the existing stream gage network.

### 2.3 Passby Flow Compliance

After a reference gage is chosen and passby flow thresholds are determined, onsite streamflow monitoring or offsite trigger gages are utilized by the Commission and project sponsors for compliance. For the Commission, the distinction between a reference gage and a trigger gage depends on how the gage is utilized. Reference gages are used to calculate streamflow statistics and determine passby flows, while trigger gages are employed for low flow monitoring and compliance. A stream gage could be inactive for some period of time and, as long as it meets the selection criteria outlined previously, still be utilized as a reference gage for performing hydrologic analyses and passby flow determinations. However, to be valid as a trigger gage, it is a prerequisite that the stream gage has to be active and reporting data in real-time. Otherwise, passby flow monitoring and compliance must be achieved using onsite streamflow monitoring at the withdrawal location or another suitable, real-time trigger gage.

Onsite streamflow monitoring requires project sponsors to install metering devices and build associated infrastructure. It is not always practical to install streamflow monitoring devices on ungaged streams due to cost, construction complexity, and difficulties with calibration and maintenance. Instead, projects often use a specified USGS real-time stream gage identified by the Commission as the trigger gage for passby flow monitoring and compliance. Projects are required to cease all withdrawals from the source stream when streamflow measured at the designated trigger gage is less than the required passby flow. For approved withdrawals located on ungaged streams, a 48-hour buffer may be required before the withdrawal, once flows exceed the passby flow thresholds, may be resumed to ensure adequate low flow protection.

## 3.0 PURPOSE AND SCOPE

In many instances, water withdrawal projects are located on ungaged streams. As stream gage locations are biased toward larger streams in the United States (Poff et al., 2006), the absence of gages on small streams with more sensitive aquatic ecosystems urges studies of ungaged flow regimes, especially for planning and regulatory purposes. Inter-annual variations of streamflow lay the foundation of aquatic habitat for biological diversity and health (Sanborn and Bledsoe, 2006). During low flow periods, balancing competing demands among diverse water use sectors and ecosystem flow needs requires sufficient knowledge of hydrologic responses to withdrawals. Diminished streamflow magnitudes are found to have a strong connection with impaired biological communities across the conterminous United States (Carlisle et al., 2010), as well as with expected results of elevated concentrations of pollutants (Bunn and Arthington, 2002).

Commission staff evaluates hydrologically similar gaged watersheds to inform reference gage selections for proposed withdrawals on ungaged streams in accordance with the LFPP. Commission passby flow determinations rely heavily on calculating streamflow statistics using reference gages and the drainage area ratio method. Yet, the effectiveness of reference gage selections has not been thoroughly investigated to date. This study aims to evaluate the predictive accuracy associated with using reference gages to estimate passby flow conditions at ungaged withdrawal sites. Twenty Commission approved withdrawal projects with passby flow requirements on ungaged streams throughout the Basin were selected for evaluation. Field discharge measurements were collected at ungaged withdrawal sites during low flow conditions for comparison with concurrent reference gage data. The cross correlation between the streamflow measurements was analyzed. Further investigations were performed regarding the reliability of passby flows generated using the drainage area ratio method versus regional regression tool outputs. The suitability of reference gage selections was assessed and the precision of estimated streamflow statistics was also examined.

## 4.0 METHODS

### 4.1 Withdrawal Site Selection

Identifying a representative sample of withdrawals with passby flows on ungaged streams was the first step in evaluating if flow conditions at a withdrawal site could be accurately estimated using a selected reference gage. This was completed by querying the Commission's HYDRA database in conjunction with utilizing GIS software. A query of the HYDRA database was conducted to identify all Commission-approved surface water withdrawals with passby flow requirements. A GIS layer of the query results was generated for further screening to ensure adequate representation of a variety of characteristics, including water use sectors, geographic distributions, hydrologic features, and watershed characteristics. Given the considerable increase in withdrawals associated with unconventional natural gas extraction in the shale formations of the Basin, it was critical to include withdrawal sites associated with this activity.

Twenty Commission-approved surface water withdrawals with passby flow requirements on ungaged streams were selected for evaluation. The drainage areas of sampled withdrawal sites ranged from 0.1 $mi^2$ to 194.8 $mi^2$. Four industry types were represented among the 20 projects, including crude petroleum and natural gas extraction, golf courses and country clubs, skiing facilities, and bottled water manufacturing. Figure 1 shows the spatial location of the 20 surface water withdrawals and corresponding reference/trigger gages. The project review and approval process associated with each of the 20 withdrawal sites used reference gages to estimate streamflow statistics. Ten of the withdrawal sites (A1 to A10) maintained an onsite measuring device to record flow and comply with applicable passby flow requirements. Table 3 includes pertinent information for withdrawal sites, with passby flows monitored using onsite flow measurements, and their corresponding reference gages. The other ten withdrawal sites (B1 to B10) monitored USGS real-time trigger gages, located outside the source stream watershed, to comply with applicable passby flow requirements. Table 4 shows relevant information for withdrawal sites with passby flows monitored using offsite trigger gages and trigger flows. Unless otherwise specified in the table, the reference gages cited were also used as trigger gages.

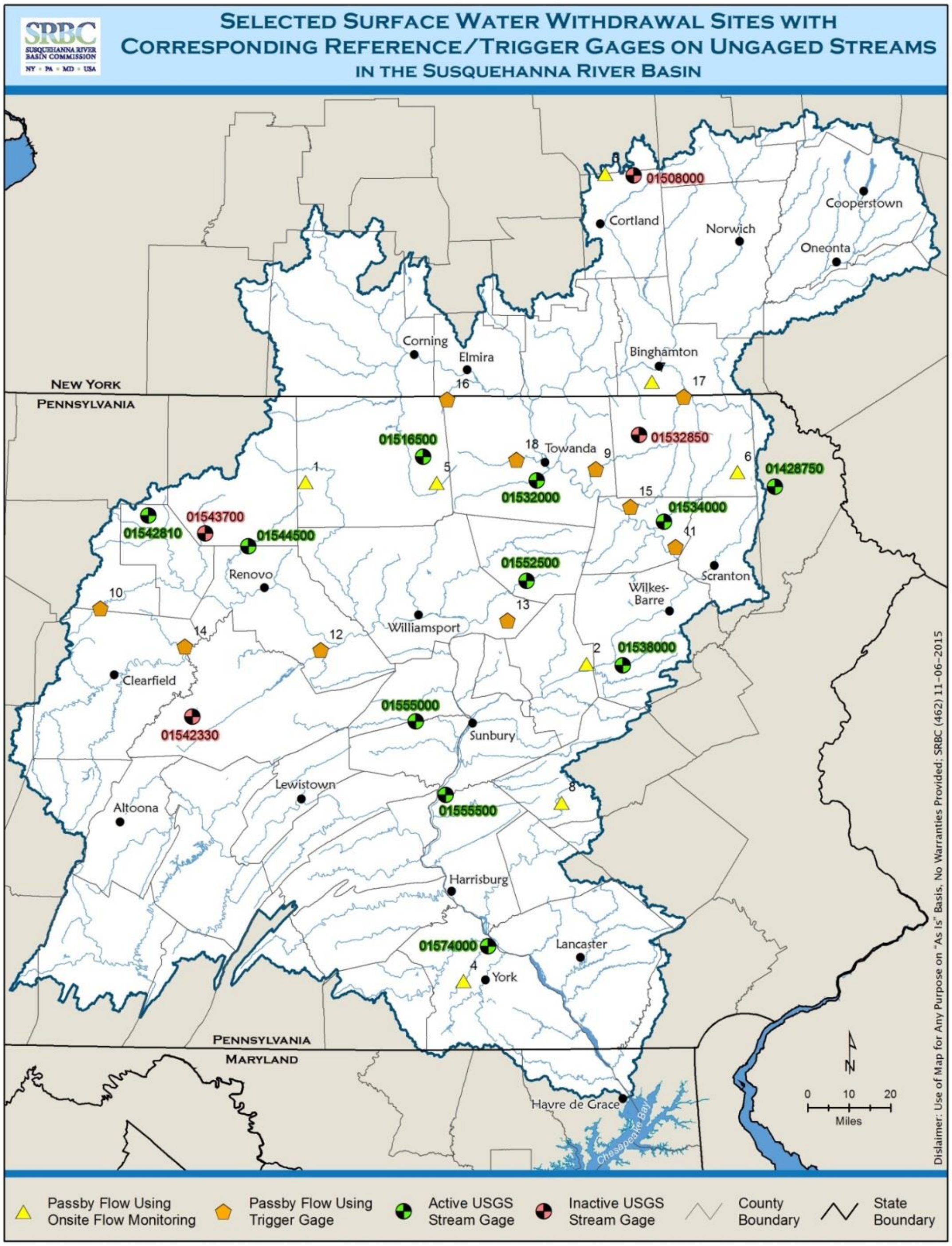



***Figure 1. Selected Withdrawal Sites with Corresponding Reference/Trigger Gages***

*Table 3. Withdrawal Sites, with Passby Flows Monitored Using Onsite Flow Measurements, and Their Corresponding Reference Gages*

| Site | Approval Date | Project Status | Project Sponsor | Industry Type | Source | Drainage Area ($mi^2$) | 7Q10 (cfs) | ADF (cfs) | Passby Flow (cfs) | Gage Station Number | Gage Station Name | Period of Record | Real-Time Status | Gage Latitude (dd) | Gage Longitude (dd) | Gage Drainage Area ($mi^2$) | Gage 7Q10 (cfs) | Gage ADF (cfs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 20081209 | Expired | EXCO Resources (PA), LLC | Crude Petroleum and Natural Gas Extraction | Unnamed Tributary to Sandy Run | 0.7 | 0.01 | 0.86 | 0.01 | 01542330 | Black Moshannon Creek near Phillipsburg, PA | 1971-1992 | Inactive | 40.87861 | -78.07667 | 2.33 | 0.04 | N/A |
| A2 | 20090631 | Expired | Ultra Resources, Inc. | Crude Petroleum and Natural Gas Extraction | Elk Run | 11.7 | 0.22 | 20.61 | 5.15 | 01542810 | Waldy Run near Emporium, PA | 1966-2002 | Active | 41.57892 | -78.29276 | 5.24 | 0.1 | 9.2 |
| A3 | 20021005 | Active | Berwick Golf Club | Golf Courses and Country Clubs | East Branch Briar Creek | 8.0 | 0.63 | 12.00 | 0.63 | 01538000 | Wapwallopen Creek near Wapwallopen, PA | 1920-2002 | Active | 41.05940 | -76.09342 | 43.8 | 3.6 | 64.8 |
| A4 | 20070901 | Active | South Slope Development Corporation - Song Mountain Ski Resort | Skiing Facilities | Unnamed Tributary to Crooked Lake | 1.0 | 0.02 | 1.74 | 0.44 | 01508000 | Shackham Brook near Truxton, NY | 1932-1968 | Inactive | 42.76740 | -76.01810 | 3.16 | 0.05 | 5.3 |
| A5 | 20081217 | Active | KBK-HR Associates LLC - Honey Run Golf Club | Golf Courses and Country Clubs | Little Conewago Creek | 21.2 | 0.45 | 24.82 | 4.96 | 01574000 | West Conewago Creek near Manchester, PA | 1930-1995 | Active | 40.08185 | -76.72028 | 510 | 10.8 | 597 |
| A6 | 20091205 | Renewed | Talisman Energy USA Inc. | Crude Petroleum and Natural Gas Extraction | Fellows Creek | 5.2 | 0.04 | 5.24 | 0.79 | 01516500 | Corey Creek near Mainesburg, PA | 1956-2002 | Active | 41.79076 | -77.01509 | 12.2 | 0.1 | 12.4 |
| A7 | 20081220 | Expired | Keystone Clearwater Solutions LLC | Crude Petroleum and Natural Gas Extraction | Upper Little Surveyor Run | 0.8 | 0.01 | 1.10 | 0.17 | 01542330 | Black Moshannon Creek near Phillipsburg, PA | 1971-1992 | Inactive | 40.87861 | -78.07667 | 2.33 | 0.04 | N/A |
| A8 | 20060303 | Active | Elk Mountain Ski Resort | Skiing Facilities | East Branch Tunkhannock Creek | 2.0 | 0.09 | 2.80 | 0.70 | 01534000 | Tunkhannock Creek near Tunkhannock, PA | 1915-2002 | Active | 41.55769 | -75.89466 | 383 | 17.5 | 542 |
| A9 | 20030402 | Active | Vestal Hills Country Club | Golf Courses and Country Clubs | Unnamed Tributary to West Fork of Little Snake Creek | 0.3 | 0.01 | 0.56 | 0.11 | 01532850 | Middle Branch Wyalusing Creek near Birchardville, PA | 1967-1979 | Inactive | 41.86270 | -76.00650 | 5.67 | 0.16 | 10.2 |
| A10 | 20020202 | Active | Log Cabin Springs | Bottled Water Manufacturing | Headwaters of Unnamed Tributary to Swatara Creek | 0.1 | 0.01* | 0.14 | 0.03 | 01555500 | East Mahantango Creek near Dalmatia, PA | 1931-2002 | Active | 40.61113 | -76.91192 | 162 | 6.3 | 228 |

* USGS gage 01572000 Lower Little Swatara Creek at Pine Grove was used for calculating 7Q10 for this site.

*Table 4. Withdrawal Sites with Passby Flows Monitored Using Offsite Trigger Gages*

| Site | Approval Date | Project Status | Project Sponsor | Industry Type | Source | Drainage Area ($mi^2$) | 7Q10 (cfs) | ADF (cfs) | Passby Flow (cfs) | Gage Station Number | Gage Station Name | Period of Record | Real-Time Status | Gage Latitude (dd) | Gage Longitude (dd) | Gage Drainage Area ($mi^2$) | Gage 7Q10 (cfs) | Gage ADF (cfs) | Trigger Flow (cfs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B1 | 20090914 | Renewed | Southwestern Energy Production Company | Crude Petroleum and Natural Gas Extraction | Wyalusing Creek | 194.8 | 8.80 | 275.00 | 55.02 | 01534000 | Tunkhannock Creek near Tunkhannock, PA | 1915-2002 | Active | 41.55769 | -75.89466 | 383 | 17.3 | 541 | 110.570 |
| B2 | 20090317 | Expired | EOG Resources, Inc. | Crude Petroleum and Natural Gas Extraction | Bennett Branch | 57.4 | 1.77 | 93.73 | 14.06 | 01543700 | First Fork Sinnemahoning Creek at Wharton, PA | 1969-2005 | Active | 41.52010 | -78.02970 | 182 | 5.6 | 297 | 44.550 |
| B3 | 20100907 | Renewed | Geary Enterprises | Crude Petroleum and Natural Gas Extraction | Buttermilk Creek | 23.6 | 0.56 | 32.40 | 6.48 | 01428750 | West Branch Lackawaxen River near Aldenville, PA | 1988-2002 | Active | 41. 67421 | -75.37609 | 40.6 | 4.9 | 77.7 | 15.700 |
| B4 | 20090906 | Renewed | LHP Management | Crude Petroleum and Natural Gas Extraction | Fishing Creek | 181.4 | 22.66 | 264.58 | 66.14 | 01555000 | Penns Creek at Penns Creek, PA | 1931-2002 | Active | 40.86673 | -77.04833 | 301 | 37.6 | 439 | 111.980 |
| B5 | 20100313 | Renewed | XTO Energy | Crude Petroleum and Natural Gas Extraction | Little Muncy Creek | 41.3 | 1.91 | 83.01 | 16.60 | 01552500 | Muncy Creek near Sonestown, PA | 1942-2002 | Active | 41.35642 | -76.53447 | 23.8 | 1.1 | 47.8 | 9.950 |
| B6 | 20100301 | Renewed | Carrizo (Marcellus), LLC | Crude Petroleum and Natural Gas Extraction | Mosquito Creek | 70.5 | 2.49 | 116.64 | 29.16 | 01544500 | Kettle Creek at Cross Fork, PA | 1942-2002 | Active | 41.47549 | -77.82573 | 136 | 4.8 | 225 | 57.390 |
| B7* | 20090628 | Renewed | Susquehanna Gas Field Services, LLC | Crude Petroleum and Natural Gas Extraction | Meshoppen Creek | 114 | 2.13 | 161.39 | 32.28 | 01534000 | Tunkhannock Creek near Tunkhannock, PA | 1915-2002 | Active | 41.55769 | -75.89466 | 383 | 17.3 | 541 | 108.660 |
| B8 | 20100914 | Renewed | Talisman Energy USA Inc. | Crude Petroleum and Natural Gas Extraction | Seeley Creek | 26.6 | 0.22 | 27.05 | 5.41 | 01516500 | Corey Creek near Mainesburg, PA | 1954-2002 | Active | 41.79076 | -77.01509 | 12.2 | 0.1 | 12.4 | 3.670 |
| B9** | 20090302 | Expired | WPX Energy Appalachia, LLC | Crude Petroleum and Natural Gas Extraction | Snake Creek | 73.4 | 1.59 | 112.00 | 22.40 | 01534000 | Tunkhannock Creek near Tunkhannock, PA | 1915-2002 | Active | 41.55769 | -75.89466 | 383 | 17.3 | 541 | 108.200 |
| B10*** | 20090604 | Renewed | Chesapeake Appalachia | Crude Petroleum and Natural Gas Extraction | Sugar Creek | 151 | 0.86 | 158.70 | 31.74 | 01532000 | Towanda Creek near Monroeton, PA | 1915-2002 | Active | 41.70710 | -76.48511 | 215 | 2.8 | 287 | 57.400 |

* B7 used USGS gage 0153300 Meshoppen Creek near Springville, PA, as the reference gage to compute flow statistics.
** B9 used USGS gage 01502780 Snake Creek near Montrose, PA, as the reference gage to compute 7Q10, while ADF was calculated using StreamStats.
*** B10 used USGS gage 01531300 Sugar Creek near West Burlington, PA, as the reference gage to compute flow statistics.

### 4.2 Streamflow Monitoring

Based on the impact of sporadic streamflow measurements on testing low streamflow statistics and hydrologic modeling (Riggs, 1972; Stedinger and Thomas Jr., 1985; Eng and Milly, 2007; Zhang and Kroll, 2007; Seibert and Beven, 2009), streamflow conditions were monitored to collect field discharge measurements for the study. Streamflow measurements were obtained during the low flow period of July through November from 2011 to 2014. A FlowTracker® Handheld Acoustic Doppler Velocimeter (ADV) was used in the field to measure and automatically calculate discharge rates using the USGS midsection method (Buchanan and Somers, 1969). The stream channel was divided equally, according to the stream width, into 20 or more sub-sections to adequately depict the irregular channel geometry. The water depth and velocity at each sub-section were recorded and used as inputs to compute partial discharge. The summation of the partial discharges along a transect equates to the total discharge of the stream. The bucket and drop leaf method were also employed for making discharge measurements in small headwater streams.

Ten streamflow measurements, during baseflow conditions, were targeted for each withdrawal site. Among these, six single measurements were to be obtained on different streamflow recessions. Additionally, two pairs of measurements were to be taken and each pair was to be obtained on the same recession. Figure 2 shows a schematic of desirable single and paired baseflow measurements. Ideally, the field discharge measurements were to be obtained well after any measurable rainfall events in the watershed upgradient of the withdrawal site. In general, for single streamflow measurements taken on individual streamflow recessions, the measurement was to be taken after at least five days of dry weather. The five days were determined on basis of Reilly and Kroll's study (2003), which designated baseflow after five days of continuous decreasing streamflow. For a pair of measurements taken on the same recession, the first measurement was to be obtained three or more days after a rainfall event and allow for two days of dry weather between measurements. To minimize diurnal fluctuations, field discharge measurements were ideally to be taken on cloudy days, as field schedules permitted. Based on these criteria, in a single year, no more than four-six measurements were able to be collected unless streamflow for that given year was extremely low.

Statistical Analysis System (SAS) codes were developed to monitor real-time streamflow at applicable reference/trigger gages. When the target conditions described above were met, emails were generated and sent to staff to initiate the coordination of field work. Staff checked short-term weather forecasts and coordinated with field staff to mobilize for collecting field discharge measurements. To increase efficiency in the field, a standard data collection form was developed for use by field crews to record the streamflow measurements and other important variables, including time, weather, continuous decreasing flow days, etc.

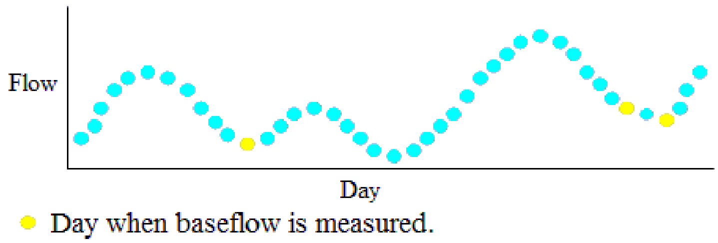



***Figure 2. Schematic of Desirable Single and Paired Baseflow Measurements***

### 4.3 Field Discharge Measurements

In order to acquire the field discharge measurements under specific baseflow conditions needed for the 20 withdrawal sites scattered throughout the Basin, four years of intermittent field work were devoted to the study. Two to eight discharge measurements were collected each year at individual sites, depending on the magnitude and frequency of rainfall events during the low flow season, as well as site access and staff availability. Since the reference gages for sites A4, A9, and B2 were not active during the study period from 2011-2014, three active USGS stream gages were assigned as their surrogate reference gages for monitoring baseflow conditions. Those stations included USGS 01509000 Tioughnioga River at Cortland, NY, USGS 01541500 Clearfield Creek at Dimeling, PA, and USGS 01543000 Driftwood Branch Sinnemahoning Creek at Sterling Run, PA. Due to the unavailability of real-time streamflow data at the reference gages for sites A4, A9, and B2, field discharge measurements were taken at both the inactive reference gage and withdrawal site on the same day. Figures 3 and 4 show staff taking discharge measurements using the FlowTracker® ADV at Little Conewago Creek (site A5) and Little Muncy Creek (site B5). Discharge measurements were not taken at sites A1 and A7 due to land access issues. In total, field discharge measurements at 18 withdrawal sites, excluding A1 and A7, were carried forward for flow correlation analysis.

***Figure 3. Discharge Measurement Taken on November 9, 2011, at Little Conewago Creek, York County, PA***

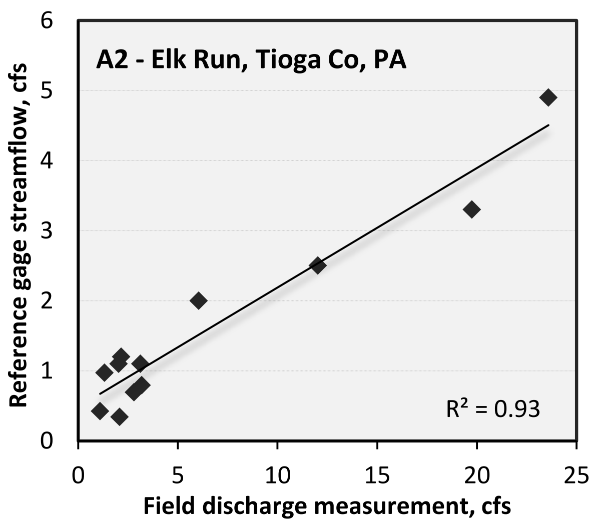
***Figure 4. Discharge Measurement Taken on July 22, 2013, at Little Muncy Creek, Lycoming County, PA***

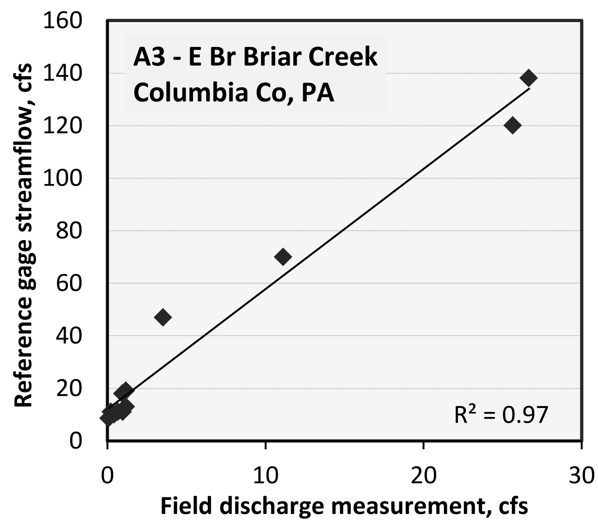
## 5.0 ANALYSIS AND RESULTS

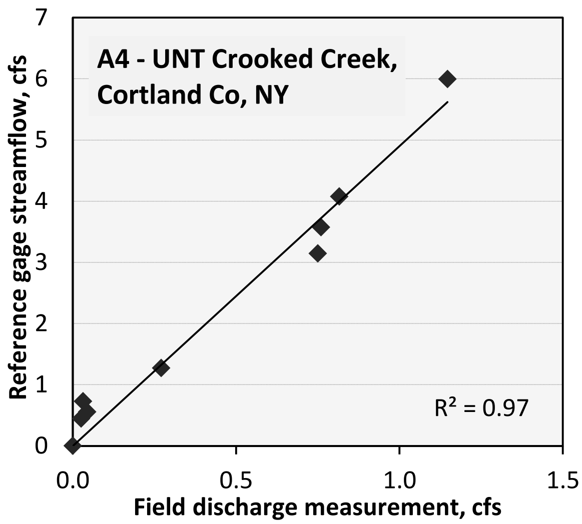
### 5.1 Reference Gage and Withdrawal Site Flow Correlations

#### 5.1.1 Commission Passby Flow Reference Gages

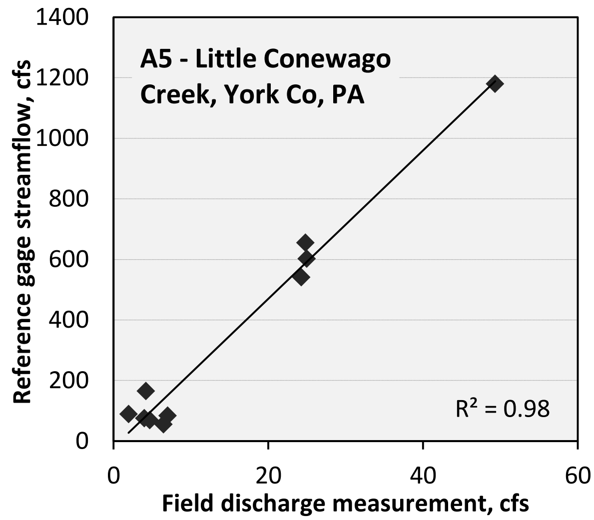
The field discharge measurements collected at the 18 withdrawal sites under baseflow conditions were plotted with concurrent streamflow values on the closest time from Commission-selected passby flow reference gages (Figure 5). In general, the periodic low flow measurements at the withdrawal sites agreed well with reference gage streamflow data. The coefficients of determination ($r^2$) were found to be greater than 0.9 for over half of the sites (11 sites) and greater than 0.8 for 17 sites. The strong flow correlation for 17 of the 18 sites revealed that the criteria the Commission used to select a reference gage and estimate low flow statistics was generally reliable. In contrast, a poor correlation was found for one of the withdrawal sites, A10. Site A10 was located in Pine Grove Township, Schuylkill County, PA, where water was withdrawn from Sweet Arrow Spring, located in the headwaters of an unnamed tributary to Swatara Creek. The reference gage used in the passby flow determination was USGS 01555500 East Mahantango Creek near Dalmatia, PA. The reference gage was located in the nearby Mahantango Creek Watershed and 28 miles to the west of A10. It was chosen primarily because of its proximity to the withdrawal site and having similar watershed characteristics to the source watershed. The potential drivers for causing the poor flow correlation will be discussed later.



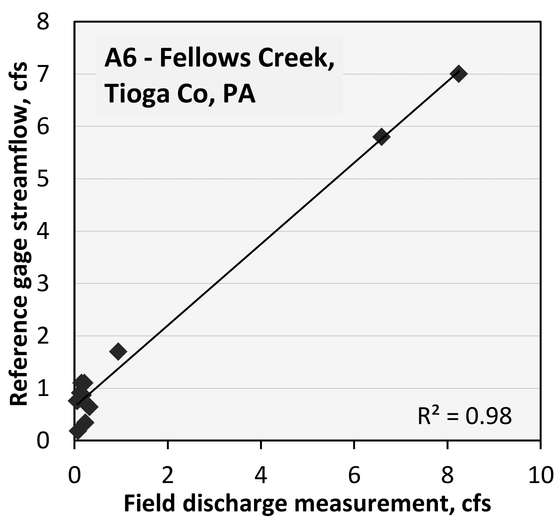





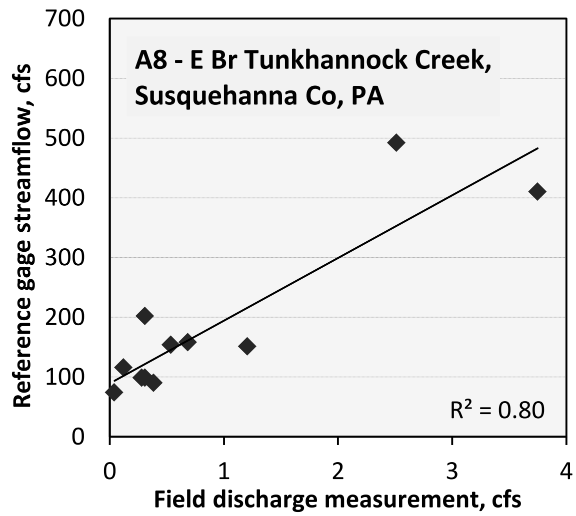
A4 - UNT Crooked Creek, Cortland Co, NY
Reference gage streamflow, cfs
Field discharge measurement, cfs
R² = 0.97

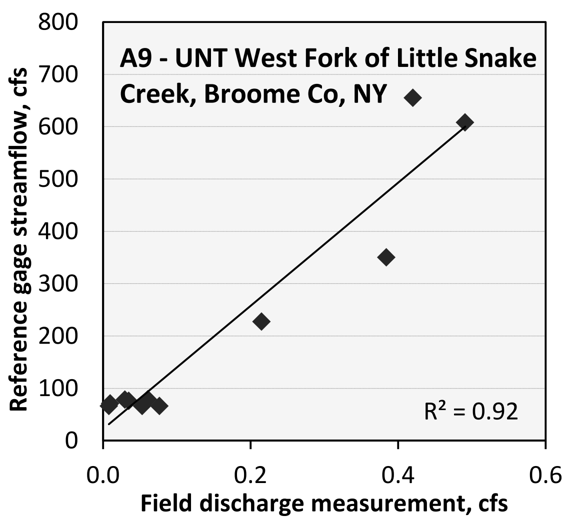
A5 - Little Conewago Creek, York Co, PA
Reference gage streamflow, cfs
Field discharge measurement, cfs
R² = 0.98

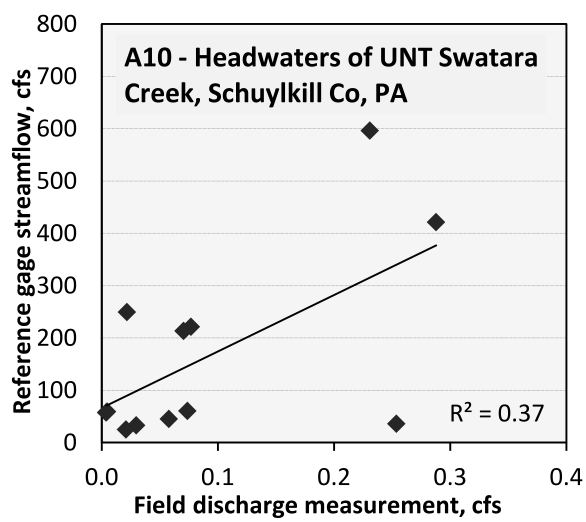
A6 - Fellows Creek, Tioga Co, PA
Reference gage streamflow, cfs
Field discharge measurement, cfs
R² = 0.98

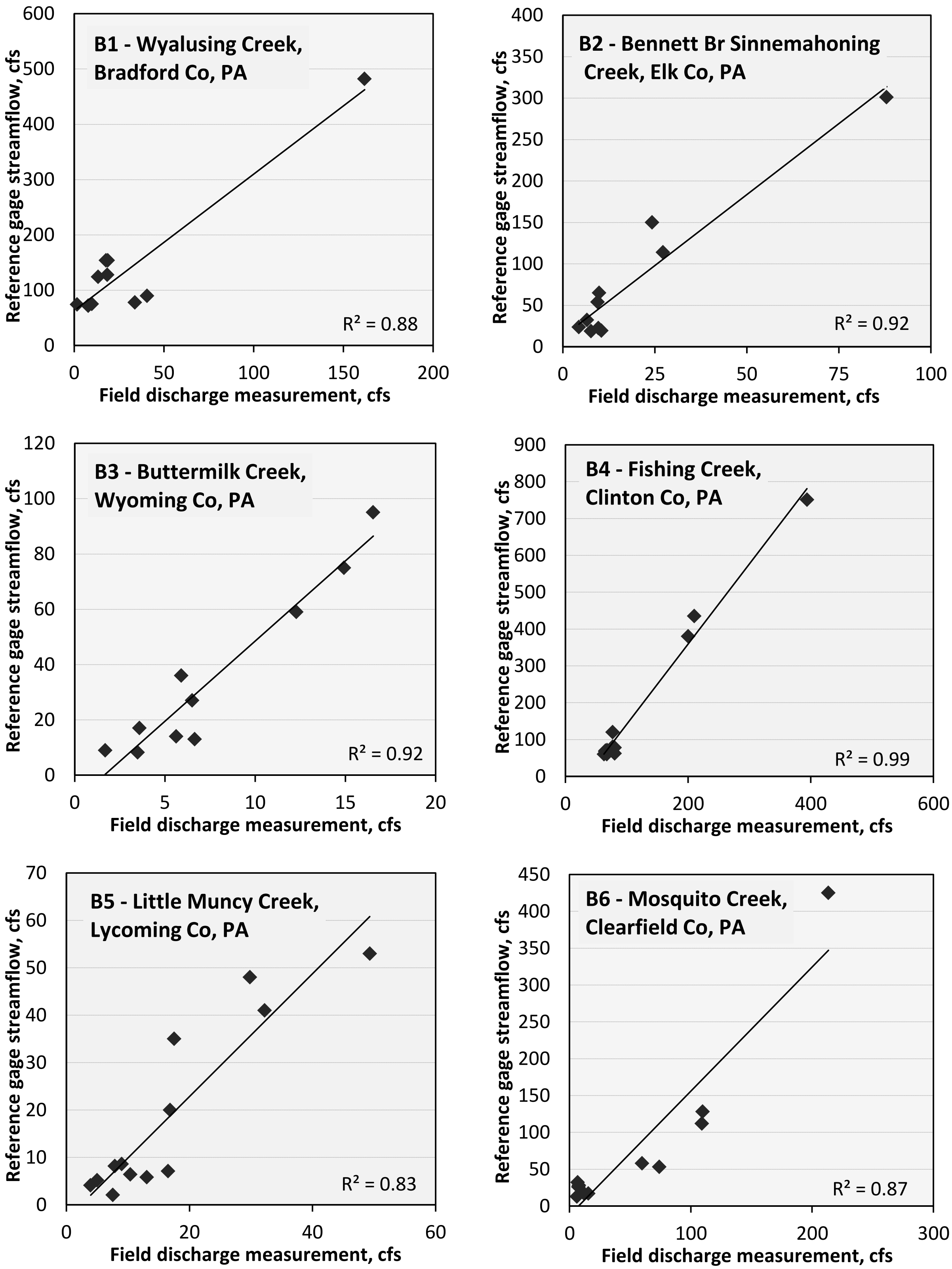
A8 - E Br Tunkhannock Creek, Susquehanna Co, PA
Reference gage streamflow, cfs
Field discharge measurement, cfs
R² = 0.80

A9 - UNT West Fork of Little Snake Creek, Broome Co, NY
Reference gage streamflow, cfs
Field discharge measurement, cfs
R² = 0.92

A10 - Headwaters of UNT Swatara Creek, Schuylkill Co, PA
Reference gage streamflow, cfs
Field discharge measurement, cfs
R² = 0.37


B1 - Wyalusing Creek, Bradford Co, PA
R² = 0.88
Reference gage streamflow, cfs
Field discharge measurement, cfs
0
100
200
300
400
500
600
0
50
100
150
200
B2 - Bennett Br Sinnemahoning Creek, Elk Co, PA
R² = 0.92
Reference gage streamflow, cfs
Field discharge measurement, cfs
0
50
100
150
200
250
300
350
400
0
25
50
75
100
B3 - Buttermilk Creek, Wyoming Co, PA
R² = 0.92
Reference gage streamflow, cfs
Field discharge measurement, cfs
0
20
40
60
80
100
120
0
5
10
15
20
B4 - Fishing Creek, Clinton Co, PA
R² = 0.99
Reference gage streamflow, cfs
Field discharge measurement, cfs
0
100
200
300
400
500
600
700
800
900
0
200
400
600
B5 - Little Muncy Creek, Lycoming Co, PA
R² = 0.83
Reference gage streamflow, cfs
Field discharge measurement, cfs
0
10
20
30
40
50
60
70
0
20
40
60
B6 - Mosquito Creek, Clearfield Co, PA
R² = 0.87
Reference gage streamflow, cfs
Field discharge measurement, cfs
0
50
100
150
200
250
300
350
400
450
0
100
200
300

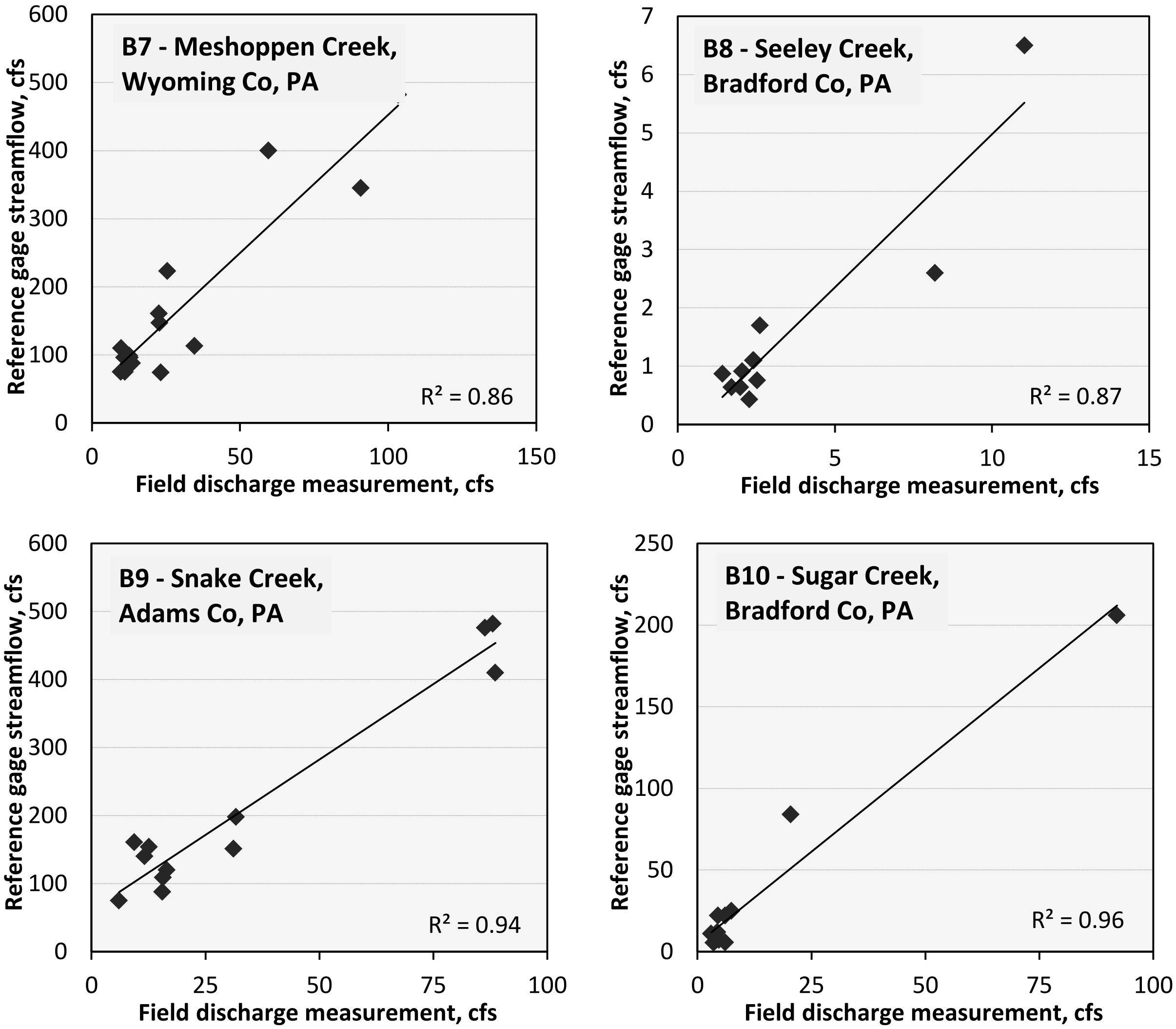



***Figure 5. Plot of Discharge Measurements at Withdrawal Sites with Concurrent Streamflow at Associated Reference Gages***

#### 5.1.2 Baseline Streamflow Estimator (BaSE) Reference Gages

The proximity of stream gages to ungaged withdrawal sites is a major factor taken into consideration when the Commission selected passby flow reference gages. In most cases, the nearest stream gage with a relatively long-term period of record was preferable if other watershed characteristics were considered similar. Yet, Archfield and Vogel (2010) noted that the selection of the nearest reference gage does not always result in the highest correlation with daily streamflow values. This has prompted introduction of the map correlation method of identifying reference gages, which has been incorporated into the Pennsylvania BaSE tool. The tool provided multiple suggestions for appropriate reference gages for a user-defined ungaged location. In the reference gage network, 156 USGS stream gages in Pennsylvania and surrounding states were assigned with a unique map of correlation estimate developed from a spherical variogram model. Ordinary Kriging was then used to interpolate correlations for the ungaged locations. The tool provided a Microsoft Excel® output file containing worksheets with reference gage information, daily flows for the reference site and ungaged location, probability exceedances for the reference site and ungaged location, and a summary report with hydrographs and flow duration curves (Stuckey et al., 2012).

In the interest of examining the effectiveness and reliability of reference gages identified using the map correlation method, the BaSE tool was run for the 20 ungaged withdrawal sites evaluated in the study. Five reference gages with the highest correlation were generated for each ungaged site. The results showed that Commission-selected reference gages for 11 of the 20 withdrawal sites were included in the list of BaSE-recommended reference gages, while the other nine sites were not. Therefore, correlation analyses between withdrawal site flow measurements and concurrent streamflow records from the top five BaSE reference gages were planned for the nine sites, for comparison with Commission-selected reference gages results. Due to a lack of field discharge measurements at sites A1 and A7, the seven remaining withdrawal sites, A2, A4, A5, A10, B2, B3, and B6, were included in the analysis. The results are summarized in Table 5. The BaSE indicated that streamflow estimates may not be valid when the distance is greater than 75 miles between an ungaged site and a reference gage. Inactive gages were also excluded from the analysis since current streamflow data were not available for comparison with field discharge measurements at ungaged withdrawal sites. Accordingly, the BaSE-recommended reference gages for site A5 were not applicable for the analysis.

The results revealed that both Commission- and BaSE-recommended reference gages for sites A2, B2, B3, and B6 exhibited strong correlations with concurrent field discharge measurements. The drainage area of site A2 is 11.7 $mi^2$. Although four BaSE reference gages, 01548500 Pine Creek at Cedar Run, PA, 01549700 Pine Creek below Little Pine Creek near Waterville, PA, 01544500 Kettle Creek at Cross Fork, PA, and 01545600 Young Womans Creek near Renovo, PA, are either in the same or a nearby watershed of A2, their drainage areas are much greater than A2, ranging from four to 80 times larger in size. The other BaSE reference gage, 01520000 Cowanesque River near Lawrenceville, PA, is located 0.5 mile downstream of Cowanesque Dam and reflects regulated streamflow conditions, which do not meet reference gage selection criteria. Considering the analogous watershed characteristics and reservoir impacts, the Commission chose the gage 01542810 Waldy Run near Emporium, PA, as the reference gage for site A2. Similarly, the drainage areas of BaSE-recommended gages for B2 are 5 to 25 times greater than the drainage area of B2. At B3, the Commission-selected reference gage presented a better flow correlation with field discharge measurements than the BaSE reference gages. At B6, BaSE reference gage 01547950 Beech Creek at Monument, PA, showed a higher baseflow correlation than the Commission-selected reference gage.

In contrast, the coefficients of determination between the BaSE reference gages and concurrent streamflow measurements were fairly low for site A4, varying from 0.13 to 0.41. A high coefficient of determination ($r^2$=0.98) was noted between the Commission-selected reference gage, USGS 01508000 Shackham Brook near Truxton, NY, and withdrawal site A4, which suggested it should be a more reliable reference gage for determining passby flows. Both Commission and BaSE-recommended reference gages exhibited low coefficients of determination with concurrent field discharge measurements for site A10, with $r^2$ values ranging from 0.32 to 0.37. This was not surprising considering the unique hydrogeologic setting associated with site A10.

*Table 5. Commission Passby Flow Gage, BaSE Reference Gages, and Withdrawal Site Flow Correlation Results*

| Site | Source | DA ($mi^2$) | Commission Passby Flow Reference Gage | DA ($mi^2$) | $r^2$ | BaSE Reference Gages | DA ($mi^2$) | $r^2$ |
|---|---|---|---|---|---|---|---|---|
| A2 | Elk Run | 11.7 | 01542810 Waldy Run near Emporium, PA | 5.2 | 0.93 | 01548500 Pine Creek at Cedar Run, PA | 604.0 | 0.91 |
| | | | | | | 01549700 Pine Creek below Little Pine Creek near Waterville, PA | 944.0 | 0.91 |
| | | | | | | 01544500 Kettle Creek at Cross Fork, PA | 136.0 | 0.85 |
| | | | | | | 01545600 Young Womans Creek near Renovo, PA | 46.2 | 0.84 |
| | | | | | | 01520000 Cowanesque River near Lawrenceville, PA | 298.0 | 0.86 |
| A4 | Unnamed tributary to Crooked Lake | 1.0 | 01508000 Shackham Brook near Truxton, NY | 3.2 | 0.98 | 0142400103 Trout Creek near Trout Creek, NY | 20.2 | 0.41 |
| | | | | | | 01423000 W Br Delaware River at Walton, NY | 332.0 | 0.13 |
| A5 | Little Conewago Creek | 21.2 | 01574000 West Conewago Creek near Manchester, PA | 510.0 | 0.98 | Not applicable | - | - |
| A10 | Sweet Arrow Spring | 0.1 | 01555500 East Mahantango Creek near Dalmatia, PA | 162.0 | 0.32 | 01472000 Schuylkill River at Pottstown, PA | 1147.0 | 0.37 |
| | | | | | | 01468500 Schuylkill River at Landingville, PA | 133.0 | 0.32 |
| | | | | | | 01470500 Schuylkill River at Berne, PA | 355.0 | 0.32 |
| | | | | | | 01471000 Tulpehocken Creek near Reading, PA | 211.0 | 0.37 |
| B2 | Bennett Branch | 57.4 | 01543700 First Fork Sinnemahoning Creek at Wharton, PA | 182.0 | 0.92 | 01543500 Sinnemahoning Creek at Sinnemahoning, PA | 685.0 | 0.99 |
| | | | | | | 03032500 Redbank Creek at St. Charles, PA | 528.0 | 0.91 |
| | | | | | | 01542500 West Br. Susquehanna River at Karthaus, PA | 1462.0 | 0.95 |
| | | | | | | 01543000 Driftwood Br Sinnemahoning Creek at Sterling Run, PA | 272.0 | 0.95 |
| | | | | | | 03010500 Allegheny River at Eldred, PA | 550.0 | 0.81 |
| B3 | Buttermilk Branch | 23.6 | 01428750 West Branch Lackawaxen River near Aldenville, PA | 40.6 | 0.92 | 01534000 Tunkhannock Creek near Tunkhannock, PA | 383.0 | 0.76 |
| | | | | | | 01538000 Wapwallopen Creek near Wapwallopen, PA | 43.8 | 0.78 |
| B6 | Mosquito Creek | 70.5 | 01544500 Kettle Creek at Cross Fork, PA | 136.0 | 0.87 | 01543000 Driftwood Br Sinnemahoning Creek at Sterling Run, PA | 272.0 | 0.87 |
| | | | | | | 01547950 Beech Creek at Monument, PA | 152.0 | 0.92 |

### 5.2 Annual Mean and Low Flow Statistics

Under former Policy No. 2003-01, the Commission determined passby flows based on two key annual flow statistics, 7Q10 and ADF, as described previously. The 7Q10 was used in the determination of *de minimis* withdrawals, and a specified percentage of ADF was typically assigned as a passby flow requirement. Both ADF and 7Q10 were estimated by choosing an acceptable USGS reference gage and applying the drainage area ratio method. To assess the reliability of the estimates for these two key streamflow statistics, the StreamStats tool was run for the 20 withdrawal sites to obtain another set of estimated 7Q10 and ADF values based on regional regression equations. The StreamStats application generated a drainage area boundary and watershed characteristics for a user-defined location, estimated various streamflow statistics through USGS-developed regression equations, and presented the results in a standard report (USGS, 2012). The two sets of 7Q10 and ADF estimations are shown in Figures 6 and 7, respectively. As seen in Figure 6, the 7Q10 estimates from both approaches agreed reasonably well, with differences of less than 3 cubic feet per second (cfs) in 19 sites, and less than 0.5 cfs in 15 sites. However, noticeable differences were observed for withdrawal site B4. While the StreamStats 7Q10 output was 60.9 cfs, the drainage area ratio method estimate was 22.7 cfs. In terms of the mean flow statistics graphed in Figure 7, the average difference of the twenty sites between the drainage area ratio method and the StreamStats regressions was 2.6 cfs. Larger deviations were detected at withdrawal sites B1, B4, B5, and B7, with a maximum percent difference of 24 percent.

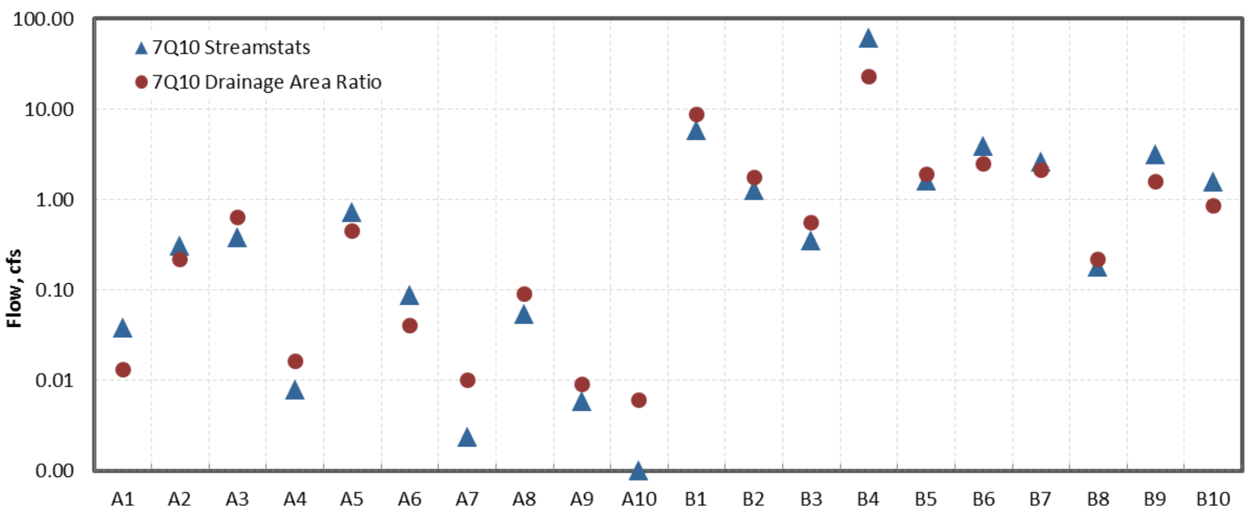



***Figure 6. Estimates of 7Q10 Flow for Withdrawal Sites Based on StreamStats Regression and Drainage Area Ratio Methods***

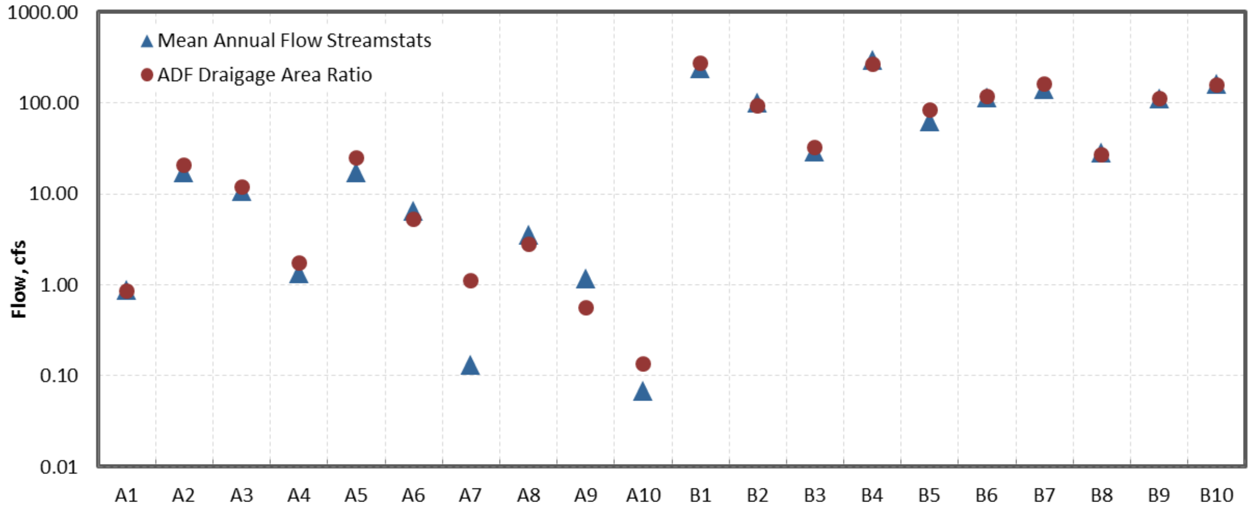



***Figure 7. Estimates of Mean Flow for Withdrawal Sites Based on StreamStats Regression and Drainage Area Ratio Methods***

### 5.3 Monthly Low Flow Statistics

In 2012, the Commission adopted the LFPP, which replaced the annual streamflow statistics (ADF and 7Q10) with monthly percent exceedance flow values as standard passby flow thresholds. The monthly passby flows were specified as monthly percentage exceedance flow values, which are determined based on stream ARCs. The approval of natural gas withdrawal projects typically expired in four years. During the study, eight withdrawal sites were renewed under the LFPP, including B1, B3, B4, B5, B6, B7, B8, and B10. To examine the accuracy of estimating new monthly passby flows, the BaSE tool was employed to generate daily streamflow time series for the ungaged sites using the top-correlated BaSE gage. BaSE estimated 17 percentiles of the FDC for an ungaged location by regional regression equations and yielded a continuous daily hydrograph from 1930 to 2008. The daily mean streamflow time series was then used to compute the same monthly percent exceedance flows. Figure 8 shows a comparison of the monthly percent exceedance passby flow thresholds computed using the reference gage drainage area ratio method and the default BaSE generated daily streamflow time series. Overall, the results agreed reasonably well among the eight ungaged withdrawal sites. The values estimated using the drainage area ratio method were 11 – 50 percent higher than the BaSE method for sites B1, B3, B5, B6, and B7, while the BaSE outputs were 23 – 34 percent greater for sites B4, B8, and B10.

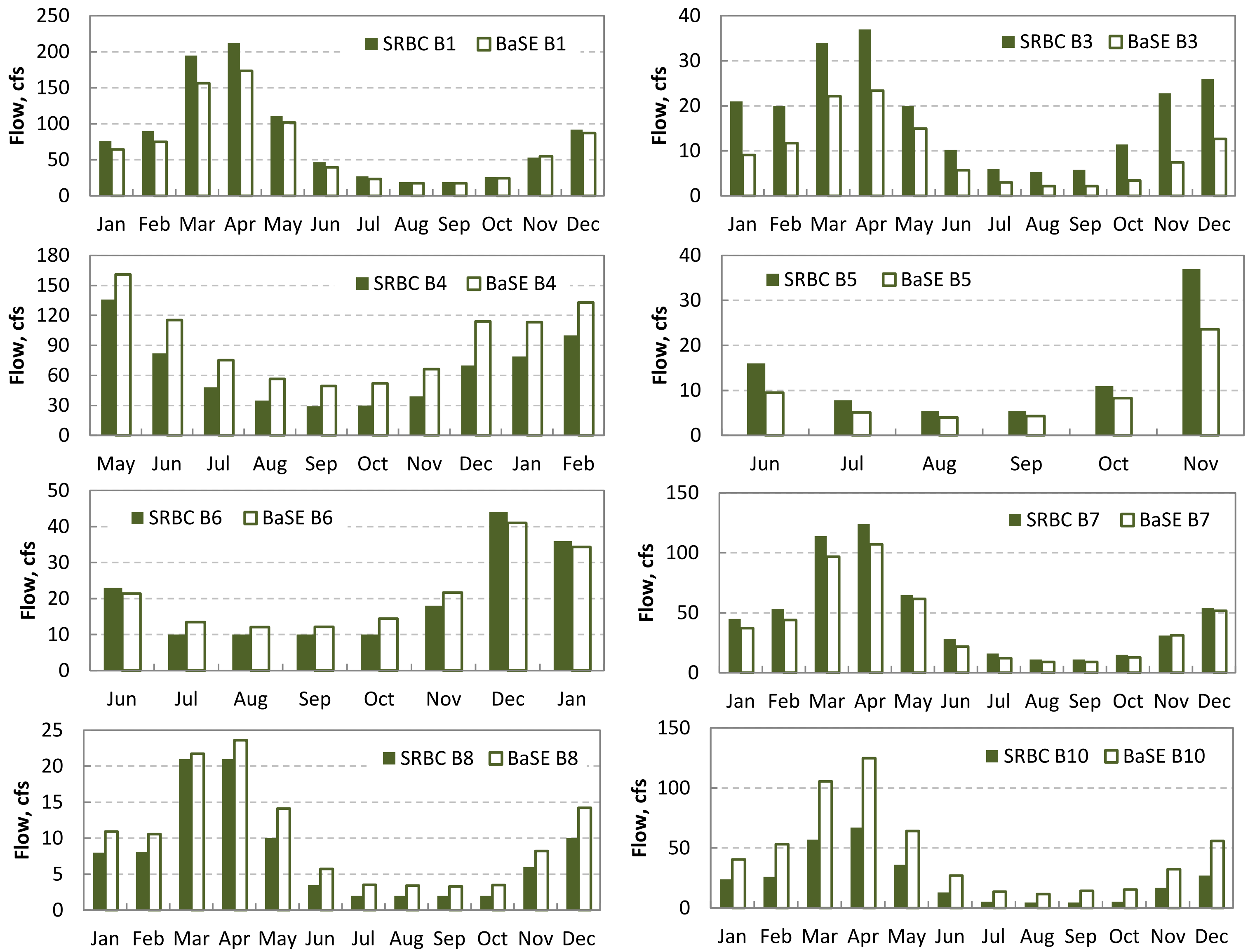



***Figure 8.*** ***Estimates of Monthly Percent Exceedance Flow Based on Reference Gage Drainage Area Ratio (Commission) and Synthesized Daily Flow Time Series (BaSE) Methods***

# 6.0 DISCUSSION

## 6.1 Discharge Measurement Accuracy

The study explored the correlation of onsite field discharge measurements with concurrent USGS streamflow data. The accuracy of streamflow measurements directly impacts confidence in performing flow correlation analyses and evaluating reference gage determinations. Most USGS gages measure stream stage and convert stage measurements to streamflow values using a stage-discharge relationship (rating curve), which is developed by physically measuring a wide range of stages and corresponding discharges (Olson and Norris, 2007). Discharge is usually computed by multiplying flow velocity by cross-sectional area, which can be obtained by using a mechanical current meter or Acoustic Doppler Current Profiler (ADCP). Baldassarre and Montanari (2009) suggest that error can originate from the imprecision of a flow meter, uncertainty in estimating cross sectional area, and imperfect development of rating curves. Furthermore, there are manmade operational biases induced via field data collection by multiple staff, as well as impacts of irregular channel geometry associated with rocks, riffles, and turbulent conditions. The USGS classifies the quality and accuracy of streamflow measurements as "excellent," "good," "fair," and "poor." "Excellent" indicates that 95 percent of the daily streamflow measurements have a maximum of 5 percent error. When 95 percent of the daily streamflow measurements have a maximum of 10 percent error, it is designated as "good." "Fair" means that 95 percent of the measurements have 15 percent or less error. If the accuracy is less than "fair," the streamflow measurement is designated as "poor." Due to the error associated with both reference gage flow and onsite field measurements, some degree of measurement uncertainty needs to be considered in the passby flow determination process.

## 6.2 Reference Gage Suitability

In order to enhance the defensibility of passby flow determinations, acknowledge uncertainty associated with hydrologic analyses, and address requirements for effective monitoring and compliance, 20 withdrawal sites with passby flow requirements in ungaged locations throughout the Basin were evaluated. For 95 percent of the assessed withdrawal sites, streamflow records from reference gages selected by the Commission presented high baseflow coefficients of determination with onsite discharge measurements. The agreement between onsite flow measurements and concurrent gage records provided evidence that the criteria employed by the Commission in selecting reference gages were effective in producing reliable estimates of low flow thresholds at ungaged withdrawal sites. The selected reference gages were found to adequately reflect the occurrence and variance of low flow events at ungaged sites during the low flow season in multiple years. However, poor low flow correlation at site A10 suggested that USGS 01555500 East Mahantango Creek near Dalmatia, PA, did not predict low flow conditions at the headwaters of an unnamed tributary to Swatara Creek with sufficient accuracy. Groundwater usually discharges to streams through a thin seepage face, where water enters from persistent, slowly varying sources (Dingman, 2015). 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 component (Smakhtin, 2001). Small springs discharge groundwater from the shallowest part of a flow system over a short period of time. The discharge rate could increase dramatically over a heavy rainfall event and decrease afterwards (Fleeger, 1999). Withdrawal site A10 is located in a small spring setting named Sweet Arrow Spring (Figure 9), while the reference gage on East Mahantango Creek near Dalmatia, PA, is located on a much larger stream system. The drainage area difference is significant and it has nonconformance with standard reference gage selection criteria. Therefore, the discrepancies between A10 and the reference gage in drainage area, groundwater discharge direction, magnitude, and timing are likely to be the primary causes of the poor flow correlation.

***Figure 9. Source for Withdrawal Site A10 at Sweet Arrow Spring, Schuylkill County, PA***

### 6.3 Flow Statistic Estimation

The Commission-selected reference gages for 11 of the 20 withdrawal sites evaluated were in agreement with BaSE-recommended reference gages, which were identified using the map correlation method. Further investigations conducted for the other seven sites using BaSE reference gages and field discharge measurements revealed high flow correlations, except for sites A4 and A10. Certain BaSE-recommended reference gages resulted in good flow correlations with onsite flow measurements that are comparable to Commission-selected reference gages, including USGS 01547950 Beech Creek at Monument, PA for withdrawal site B6, and could be considered as alternative reference gages for passby flow determination and compliance. The StreamStats and BaSE applications were shown to be effective in determining key streamflow statistics, including 7Q10, ADF, and monthly percent exceedance flow values, at ungaged sites based on their agreement with drainage area ratio method results. However, the drainage area ratio for BaSE-recommended reference gages and ungaged withdrawal sites tends to be unacceptably large, which could reduce confidence in applying the drainage area ratio method for these gages to estimate streamflow statistics. In some cases, streamflow statistics estimated using regression equations could result in significant prediction error. For example, the standard error associated with the StreamStats regression for estimating 7Q10 for central Pennsylvania streams can be as large as 51 percent (Stuckey, 2006).

## 7.0 CONCLUSIONS

Selection of appropriate reference gages for performing hydrologic analyses at ungaged withdrawal sites is critical in determining passby flow thresholds and monitoring adherence to low flow protection requirements. This study introduced an effective method for examining the performance of selected reference gages with respect to calculating passby flow values and tracking low flow conditions at ungaged withdrawal sites. The key conclusions from the study are summarized below:

- Commission-selected reference gages for determining and monitoring passby flow requirements at 17 of 18 ungaged withdrawal sites were found to perform reasonably well based on flow correlation analyses using withdrawal site discharge measurements and concurrent stream gage data, which highlights the effectiveness of suitable reference gages in passby flow implementation.

- A poor flow correlation between the Commission-selected reference gage and field discharge measurements for 1 of 18 ungaged withdrawal sites was attributed to significant differences in drainage area size and hydrogeologic setting, which emphasizes the importance of adhering to accepted reference gage selection criteria.

- The majority of Commission-selected reference gages (11 of 20) for ungaged withdrawal sites were found to be in agreement with the highest correlated stream gages identified using the map correlation method in the BaSE application, which corroborates the Commission's reference gage selection methodology.

- Flow correlation analyses for the other six available of 20 ungaged withdrawal sites revealed that the most highly correlated BaSE reference gages performed reasonably well for four of the sites, but performed poorly for two others, which underscores the importance of drainage area size, reservoir regulation impacts, and local precipitation patterns in selecting reference gages for passby flow implementation.

- Passby flow thresholds computed for ungaged withdrawal sites using regression-based tools, including the StreamStats and BaSE applications, were found to be in reasonable agreement with those calculated using the reference gage drainage area ratio method, which suggests these tools can be used as comparative methods for determining or validating passby flow thresholds for ungaged locations.

## 8.0 RECOMMENDATIONS

The methods, results, and conclusions presented in the preceding sections guided the development of a series of study recommendations. The recommendations were designed to further enhance the Commission's existing processes with respect to selection of suitable reference gages, and calculation of passby flow thresholds, for implementing low flow protection at ungaged withdrawal sites. They are expected to serve as a guide for Commission staff, partner agencies, project sponsors, and consultants involved in assessing passby flow requirements. The primary recommendations from the study are outlined below:

- Continue to utilize USGS reference stream gages as a reliable, low impact, and cost-effective means of determining and monitoring passby flow requirements at ungaged withdrawal sites.

- Exercise caution in designating trigger gages for passby flow monitoring and compliance at ungaged withdrawal sites located in very small or unique hydrologic/geologic settings, where onsite monitoring may be the only reliable means of ensuring low flow protection objectives are met.

- Continue to adhere to and, where appropriate, amend standard reference gage selection criteria for making passby flow determinations and specifying associated low flow monitoring and compliance requirements at ungaged withdrawal sites.

- Utilize regression based tools, including the USGS StreamStats and BaSE applications, as comparative methods for informing reference gage selections and calculating passby flow thresholds for ungaged withdrawal sites, particularly those located in gaps within the existing reference gage network.

- Incorporate rounding when designating passby flow thresholds, considering discharge measurement accuracy, rating curve limitations, drainage area ratio method assumptions, regression equation standard error, and ecosystem flow needs uncertainty.

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