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ESTIMATED GROUNDWATER AVAILABILITY IN THE DELAWARE RIVER BASIN 2020–2060

Technical Report No. 2022-5

Managing, Protecting and Improving
the Water Resources of the
Delaware River Basin since 1961

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Estimated Groundwater Availability in the Delaware River Basin 2020–2060

DRBC Report No: 2022-5

Prepared by Michael Y. Thompson, Sara C. Sayed, Sarah Beganskas and Chad E. Pindar

Authorization

This work is being conducted in accordance with Article 3 Section 3.6.c of the Delaware River Basin Compact (PL 87-328, 75 Stat. 688). More specifically, it is part of a broader project termed "*Water Supply Planning for a Sustainable Water Future 2060",* which has been approved in annual DRBC Water Resources Programs, most recently for FY2022-2024 (DRBC, 2021).

Acknowledgements

We would like to acknowledge the help and expertise of the following agencies in the development of this report: Delaware Department of Natural Resources and Environmental Control (DNREC), New Jersey Department of Environmental Protection (NJDEP), Pennsylvania Department of Environmental Protection (PADEP), the United States Geological Survey's Pennsylvania Water Science Center (USGS-PWSC) and the Commission's Water Management Advisory Committee.

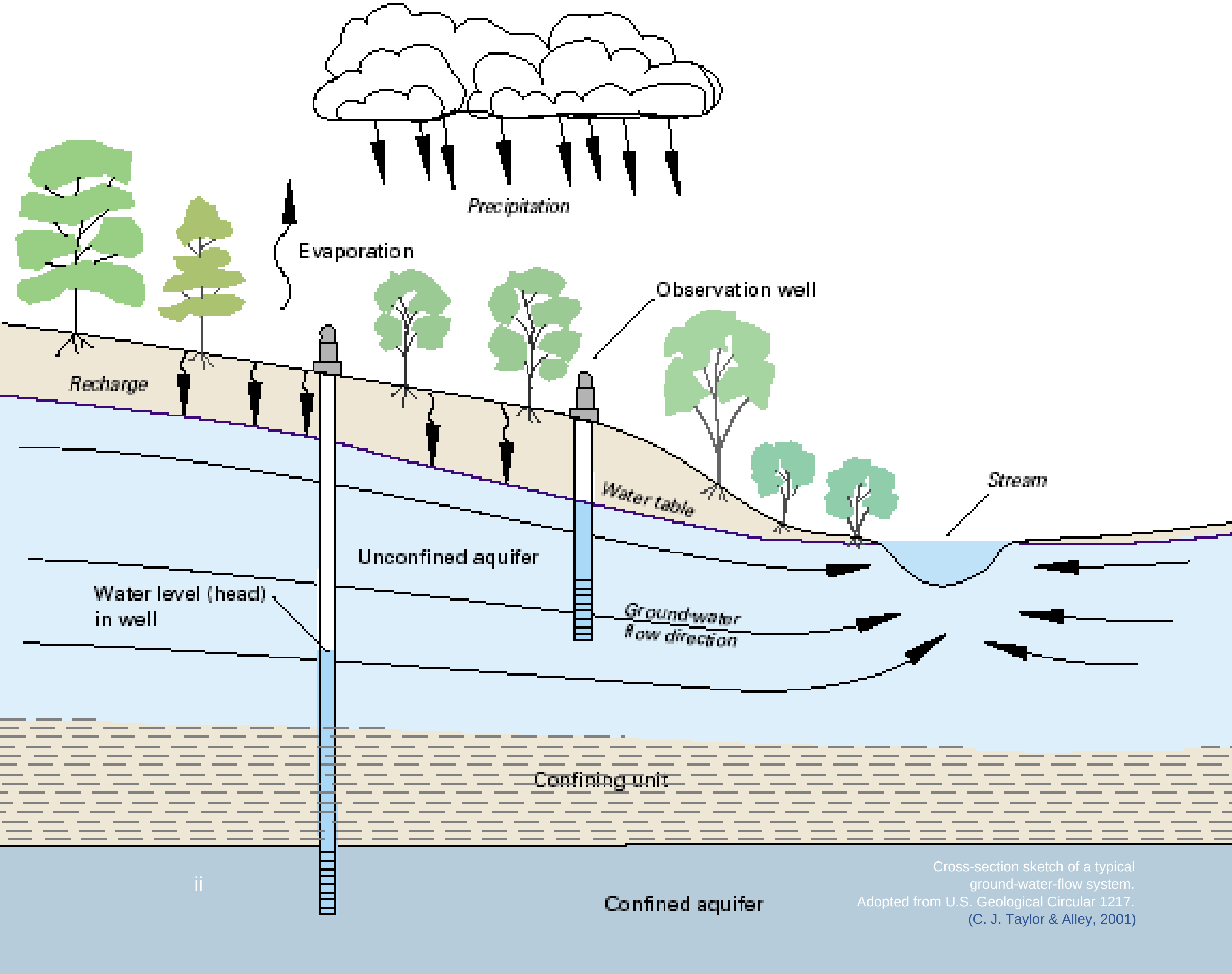
This work was funded in part by the U.S. Fish and Wildlife Service (FWS) through the National Fish and Wildlife Foundation's (NFWF) Delaware Watershed Conservation Fund (DWCF), grant number 72417. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government or the National Fish and Wildlife Foundation and its funding sources. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Government, or the National Fish and Wildlife Foundation or its funding sources

Scope and Organization

The purpose of this study is to assess current and projected groundwater availability in the Delaware River Basin. A detailed background of the applied screening methodology is provided along with a thorough description of the Basin's hydrologic setting through a lens focused on hydrogeology. The results of the groundwater availability screening tool are presented for two assessment scales: (1) the entire Basin, and (2) the Southeastern Pennsylvania Groundwater Protected Area. Specific limitations of the methodology are addressed in a manner not previously done by the Commission. The results are tied into discussions on trends in available natural resources over time (streamflow and groundwater levels), possible impacts of climate change, and the seasonal patterns of annual data. This work fits within the Commission's broader focus on water security – working to ensure sustainable supplies of suitable quality water for the Delaware River Basin.

“For the Delaware is a gentle river, gracious and inviting;
its charms are never-ending; and, surely, those who see
its glories never can forget the river’s beauty.”

\- Harry Emerson Wildes, 1940



Cross-section sketch of a typical
ground-water-flow system.
Adopted from U.S. Geological Circular 1217.
(C. J. Taylor & Alley, 2001)

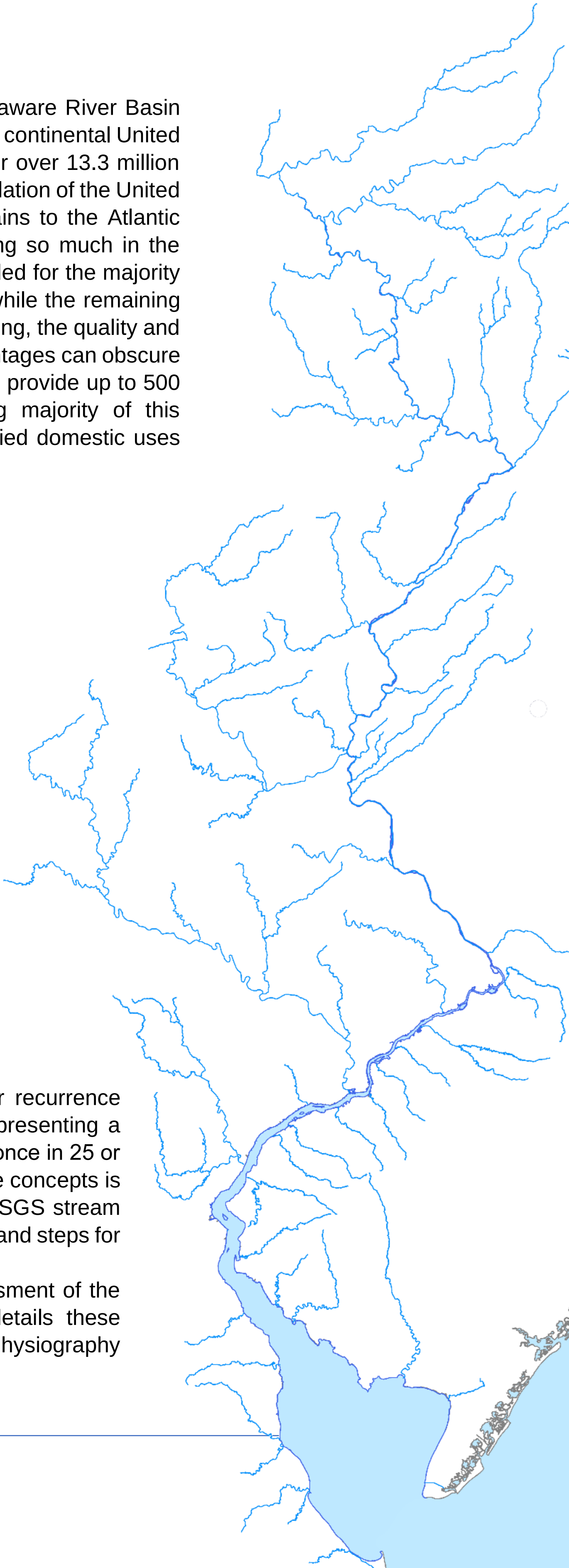
Executive Summary

Water is an essential component of life. Although the Delaware River Basin (DRB or Basin) drains only four-tenths of one percent of the total continental United States land area, its water resources provide drinking water for over 13.3 million people in four states—approximately 4 percent of the total population of the United States. As the mainstem river flows from the Catskill Mountains to the Atlantic Ocean, it is often the recipient of justified praise for sustaining so much in the region; within the Basin, surface waters have historically provided for the majority (upwards of 95%) of human water use since the 1990s. And while the remaining 5% provided by groundwater might initially appear underwhelming, the quality and necessity of such water cannot be overstated. Reports in percentages can obscure groundwater's total value – the Basin's groundwater resources provide up to 500 million gallons per day for human use. The overwhelming majority of this groundwater is used for public water supply (54%), self-supplied domestic uses (22%) and irrigation (8%).

This study performed by the Delaware River Basin Commission (DRBC) assesses the availability of groundwater resources within the Basin. It focuses primarily on baseflow, which is the amount of water in a stream or river that is assumed to come from groundwater sources. Previous studies have analyzed United States Geological Survey (USGS) stream gages throughout the Basin to calculate estimated baseflow using a process called "hydrograph separation." While a hydrograph provides a time-series of stream flow values, the process of hydrograph separation splits this time-series into components of baseflow, and stormwater runoff. The resulting baseflow time-series were used to calculate "baseflow recurrence intervals," which represent the amount of time expected to occur between low stream baseflow events (i.e., low groundwater flow to the stream.) For example, a baseflow expected to occur only once every 25 years would be said to have a "25-year recurrence interval" (abbreviated in this report as RI-25.) The baseflow recurrence intervals for specific USGS stream gages were then used to determine baseflow recurrence intervals for 147 subbasins (i.e. small watersheds) which cover the entire Basin.

Specifically, this study focuses on baseflow at a 25-year recurrence interval (RI-25) and a 50-year recurrence interval (RI-50), representing a stream's low baseflow condition that is expected to occur only once in 25 or once in 50 years, respectively. A background summary of these concepts is discussed within Section 2 of the report, providing example USGS stream gage annual data, example hydrograph separation techniques, and steps for baseflow recurrence interval calculation.

Following the discussion on availability metrics, an assessment of the hydrologic setting is provided in Section 3. This section details these characteristics through a hydrogeologic lens, focusing on the physiography



and rock type in the northern portion of the Basin and the confined aquifer network composition of the Coastal Plain. Once an understanding of available groundwater resources is established, this section highlights the groundwater withdrawal demands on those resources. Historical and projected groundwater withdrawals from the Delaware River Basin are adopted from a prior DRBC study and adjusted to reflect the concept of “net withdrawals”. These two sources of data, (1) natural resource availability and (2) net groundwater withdrawals, are the primary components in the methodology to assess groundwater availability, as discussed in Section 4. Withdrawals from two planning scales (1) Basin-wide, which is comprised of 147 subbasins, and (2) the Southeastern Pennsylvania Groundwater Protected Area (SEPA-GWPA), which is comprised of 76 subbasins, are represented as a percentage of the available baseflow at 25- and 50-year recurrence intervals. Analysis in this section demonstrates that the Basin-wide assessment methodology is not appropriate for many subbasins in the Coastal Plain, where the majority of withdrawals are from the confined aquifer network, which contravenes the limitations and assumptions stated in the baseflow availability studies.

Results from this groundwater availability screening tool are discussed in Section 5 and indicate that groundwater resources are being used at sustainable rates in most of the Delaware River Basin (confined aquifers in the Coastal Plain were not assessed.) At the Basin-wide scale, projected net groundwater withdrawals from only one subbasin (the Little Lehigh Creek, Pa.) extended beyond 75% of the either the RI-25 or RI-50 baseflow and did so based on the upper 95% predictive interval associated with the projected net groundwater withdrawal. Assessment of the SEPA-GWPA showed that two subbasins show existing or projected net groundwater withdrawals above the RI-25 and RI-50 baseflows: subbasins SP-03 (Pine Run in the Neshaminy Creek headwaters) and SP-29 (Crow Creek in the Schuylkill River watershed). More detailed assessments considering additional factors such as well depth and local geologic features were performed, which did not reveal localized issues in either subbasin.

Considering the results of screening for groundwater availability issues, Section 6 examines whether natural resources have responded to groundwater management efforts and/or human demands. Recent findings from a USGS study on stream low flow trends in the Delaware River Basin suggest that annual average 7-day low flow volumes have been increasing in much of the Basin and decreasing flows in parts of the Coastal Plain. These results are promising: An observed increase in low flows supports the conclusion that groundwater use has been sustainable—otherwise, low flows would have been expected to decrease along with declining groundwater levels. The low flow study also noted that detailed groundwater trend work was not available and would be valuable. To this end, this study assesses available groundwater level data and, based on this limited analysis rising groundwater levels in much of the Basin are consistent with the increasing stream low flow trends.

The possible effects of climate change on groundwater resources in the Delaware River Basin are briefly reviewed in Section 7, and a possible methodological advancement to consider seasonality in both recurrence intervals and withdrawals is discussed in Section 8. The findings and content of this study represent a significant step forward in the overall planning process for assessing groundwater availability in the Delaware River Basin.

Often, when conducting studies, researchers are subject to external constraints such as time, funding, and the intended application. Consequently, there is often room for improvement in most studies. This research is no different, and it is intended that the methods used in this study are a framework for future studies. As such, multiple recommendations for future improvements are provided in Section 9.

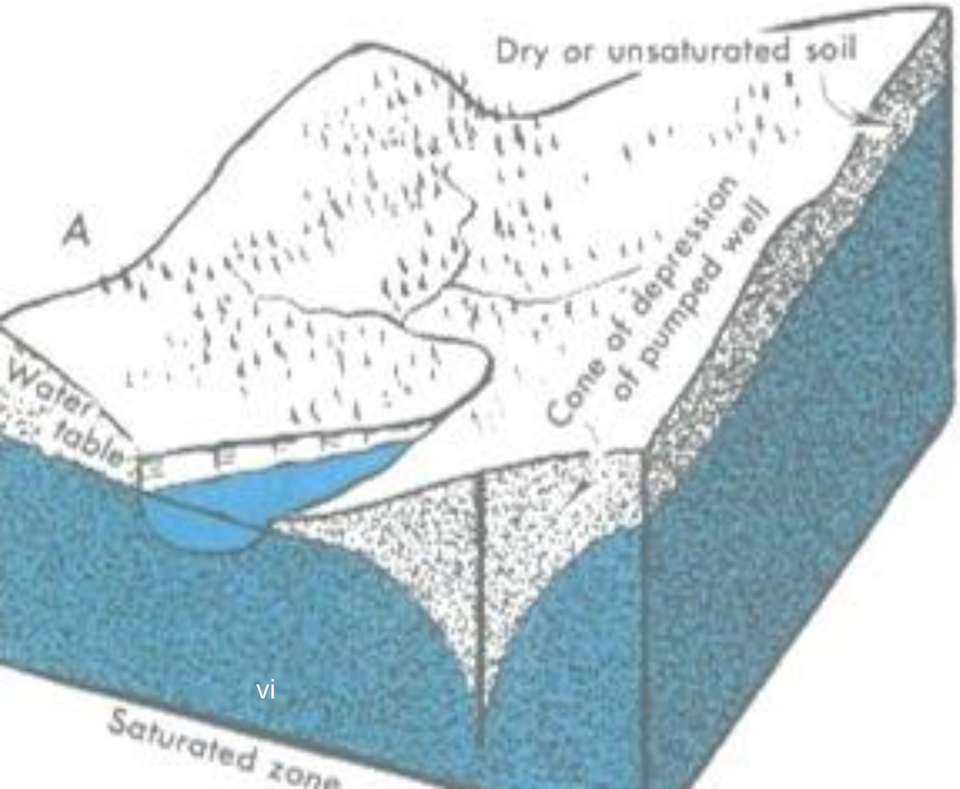
List of Acronyms/Abbreviations

80%PI	predictive interval (80th percentile)
95%PI	predictive interval (95th percentile)
CU	consumptive use
CUR	consumptive use ratio
CY	calendar year
DE DNREC	Delaware Department of Natural Resources and Environmental Control
DGS	Delaware Geological Survey
DoR	Drought of Record
DRB	Delaware River Basin
DRBC	Delaware River Basin Commission
ESRI	Environmental Systems Research Institute
FY	fiscal year
GIS	geographical information system
GPM	gallons per minute
GW	groundwater
HUC	hydrologic unit code
HYSEP	hydrograph separation program
IND	Industrial (water withdrawal sector)
IRR	Irrigation (water withdrawal sector)
KRA	Key Result Area
MG	million gallons
MGD	million gallons per day
MGM	million gallons per month
MGY	million gallons per year
MIN	Mining (water withdrawal sector)
MM	million
NJDEP	New Jersey Department of Environmental Protection
NWIS	National Water Information System
NYSDEC	New York State Department of Environmental Conservation
OTH	Other (water withdrawal sector)
PADEP	Pennsylvania Department of Environmental Protection
PA DCNR	Pennsylvania Department of Conservation and Natural Resources
RI	Recurrence interval
RI-25	25-year recurrence interval
RI-50	50-year recurrence interval
PWR	Power Generation (water withdrawal sector)
PWS	Public Water Supply (water withdrawal sector)
SEPA-GWPA	Southeastern Pennsylvania Groundwater Protection Area
SRBC	Susquehanna River Basin Commission
SSD	Self-Supplied Domestic (SSD)
Stat.	Statute
SW	surface water
USACE	U.S. Army Corps of Engineers
USCB	U.S. Census Bureau
USGS	U.S. Geologic Survey
WMAC	Water Management Advisory Committee

A note on nomenclature:

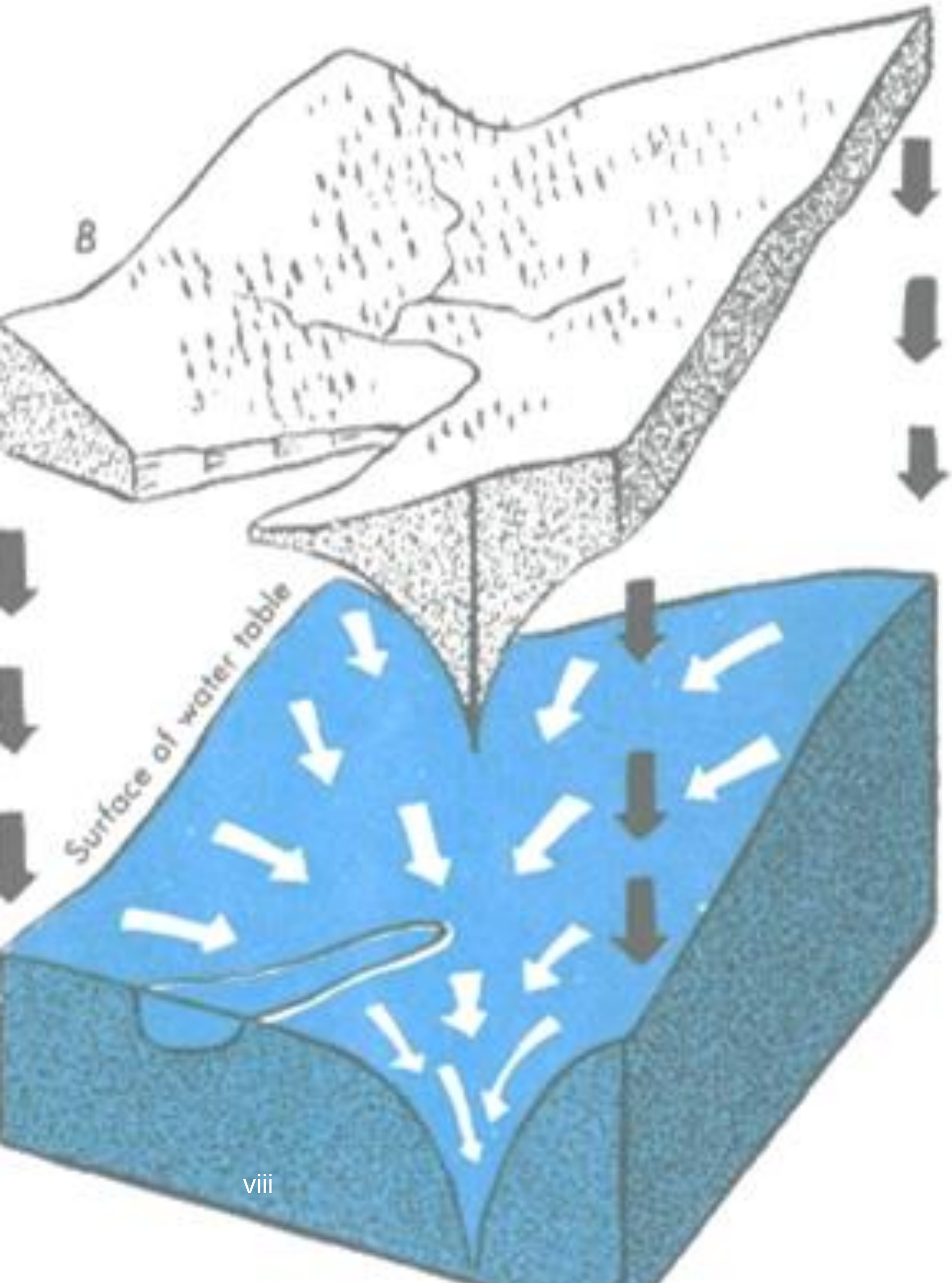
The Commission's rules adopted by Resolution No. 80-18 (as amended by Resolutions Nos. 80-27, 82-5, 85-1, 86-13, 98-1, and 99-11) appear in the Commission's Administrative Manual under the heading, "Ground Water Protected Regulations—Southeastern Pennsylvania" and in Title 18 of the Code of Federal Regulations (the "C.F.R.") as "Part 430—Ground Water Protection Area: Pennsylvania." Different numbering systems are used in the respective codes. Throughout this document, the regulations will be referred to as the "Protected Area Regulations," and specific provisions of the regulations will be referenced by their C.F.R. citations (e.g., "18 C.F.R. § 430.1").

Notably, in the heading assigned the Protected Area Regulations by both the Commission's Administrative Manual and the C.F.R., as well as in the provisions comprising these regulations, the term "ground water" appears as two words. Today, the single word "groundwater" is preferred and much more commonly used. Accordingly, except where quoting the language of the regulations directly, the authors use "groundwater." The phrase "ground water" is used in direct quotations of the rules for accuracy.



Effect on local water table of pumping a well. Adopted from the 1960 USGS report "*A Primer on Water*". (Leopold & Langbein, 1960)

Table of Contents



Dry surface lifted up to show surface of saturated zone. Adopted from the 1960 USGS report "*A Primer on Water*". (Leopold & Langbein, 1960)

1. INTRODUCTION

1.1. Study purpose and authority

The purpose of this study is to analyze groundwater availability for the Delaware River Basin (DRB or Basin) and to provide projected groundwater availability estimates through the year 2060 in support of water supply planning. The primary result is the identification of subbasins that are projected to approach or exceed subbasin withdrawal thresholds. This work is being conducted in accordance with Article 3 Section 3.6.c of the Delaware River Basin Compact (PL 87-328, 75 Stat. 688).

More specifically, this work is related to initiatives set forth in the *Water Resources Plan for the Delaware River Basin*, henceforth referred to as the "*Basin Plan*" (DRBC, 2004). The *Basin Plan* includes five interrelated Key Result Areas (KRA) which outline desired results for the Basin. The first KRA is "Sustainable Use and Supply", which calls for an adequate and reliable supply of suitable quality water to sustain human and ecological needs. Under this KRA-1, Goal 1.3 is specifically focused on ensuring that there is an adequate and reliable supply of water given the current demands in each water use sector, as well as future demands based on projections of future water use. The Commission's most recent Water Resources Program (FY2022–2024) section 2.2.1.1.1 calls for a "*detailed and comprehensive analysis of water demand, availability and sufficiency through 2060*" (DRBC, 2021). Furthermore, the Commission's 2060 Sustainable Water Supply workplan includes a task to compare projected groundwater withdrawals against the 25-year and 50-year recurrence interval baseflows at the Basin-wide and Southeastern Pennsylvania Groundwater Protected Area (SEPA-GWPA) scales. This study will further help the Commission's mission of water security for the 13 million Americans who rely on the Basin's waters.

Water availability within the Basin was assessed in a 2008 joint study performed between the U.S. Army Corps of Engineers (USACE) and the DRBC, termed the "*Multi-jurisdictional Report*" (USACE & DRBC, 2008). The report includes an estimate of water use within the Basin for the year 2003, projections of each water use sector's peak monthly water withdrawal to the year 2030, and comparisons of demand versus availability. However, a limitation of this project is that it did not account for the 1961–1967 drought of record (DoR), which is specified in Section 2.4.1 of the DRBC Water Code to be "*the basis for determination and planning of dependable Basin water supply*" (18 C.F.R. Part 410). This limited the Commission's understanding of the amount of available groundwater during a drought of record and whether supply would be adequate in a long-term drought. The current study includes an analysis of groundwater use against the 50-year recurrence interval baseflow in order to improve our understanding of groundwater availability during more extreme hydrologic conditions such as a repeat of the DoR.

In this study, an assessment of Basin-wide groundwater availability through the year 2060 is provided to identify areas projected to approach or exceed the groundwater withdrawal limits established within the SEPA-GWPA and/or recurrence-interval baseflows identified for 147 subbasins comprising the entire Basin. Identified areas of potential exceedance may warrant additional analyses and collaboration with partners. Results of this study will help provide a baseline for future planning objectives in the Basin.

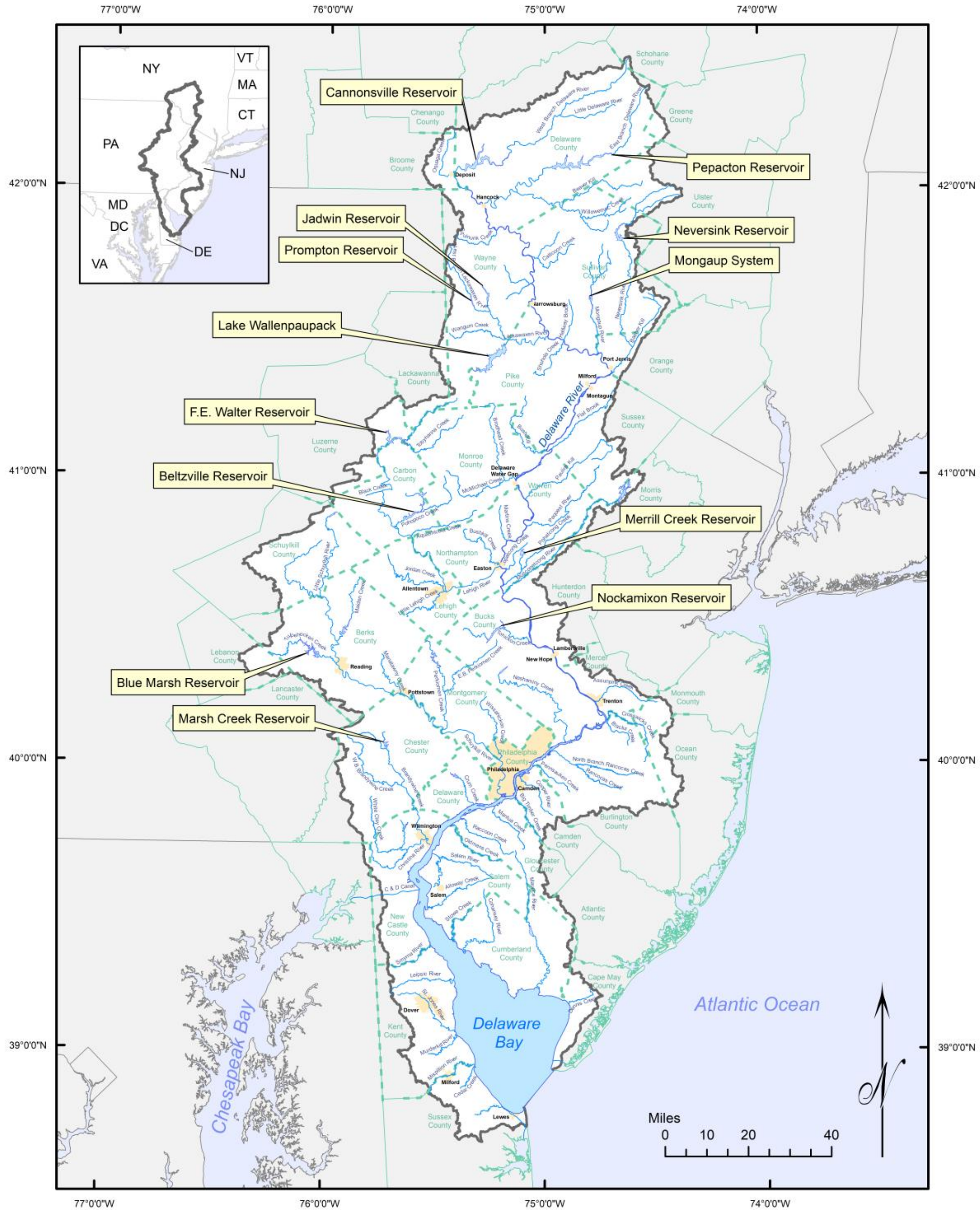


Figure 1: A map of the Delaware River Basin showing state borders (gray lines), county boundaries (green lines), cities and towns (orange shading), major rivers (blue), and reservoirs (yellow boxes). Note that the approximately eight square miles of Maryland are not included in this study.

1.2. Basin background

The Delaware River Basin, located in the northeastern United States, covers an area of approximately 13,539 square miles, spanning four Basin States as shown in Figure 1. The headwaters of the Basin originate in the western Catskill Mountains, which reach elevations from 2,500 to over 3,800 feet above mean sea level. The mainstem Delaware River officially begins at the confluence of the East and West Branches in Hancock, NY, and flows approximately 330 miles until it joins the Atlantic Ocean. Along the way, the river is fed by 216 major tributaries, draining portions of New York (2,395.1 mi^2, 18.6%), Pennsylvania (6,454.0 mi^2, 50.2%), New Jersey (3,009.5 mi^2, 23.4%), and Delaware (978.7 mi^2, 7.6%). While the mainstem Delaware River is one of the longest free flowing rivers in the country, there are numerous impounded reservoirs throughout the Basin located on its tributaries. The use of reservoirs may be singular or multi-purpose; typical uses include water supply, flood control, hydroelectric power, and recreation.

Overall, the Delaware River Basin provides a wide array of benefits for those who depend on it. Three quarters of the non-tidal Delaware River are included in the National Wild and Scenic Rivers System, as well as one tributary and portions of many other tributaries (DRBC, 2020). To receive this recognition, a body of water is recognized as possessing “*outstandingly remarkable scenic, recreational, geologic, fish and wildlife, historic, cultural or other similar values*” (Pub. L. No. 90-542, 82 Stat. 906). Economically, the Basin annually supports billions of dollars in industries such as navigation, agriculture, water supply, fish/wildlife, and recreation (Kauffman, 2011). Finally, the Delaware River Basin is estimated to supply drinking water for an estimated 13.3 million people based on 2016 data, including 8.3 million people residing within the Basin and 5 million people who rely on water exported to New Jersey and New York City (Byun et al., 2019).

A map of the Delaware River Basin
Adopted from the 1964 DRBC Annual Report.

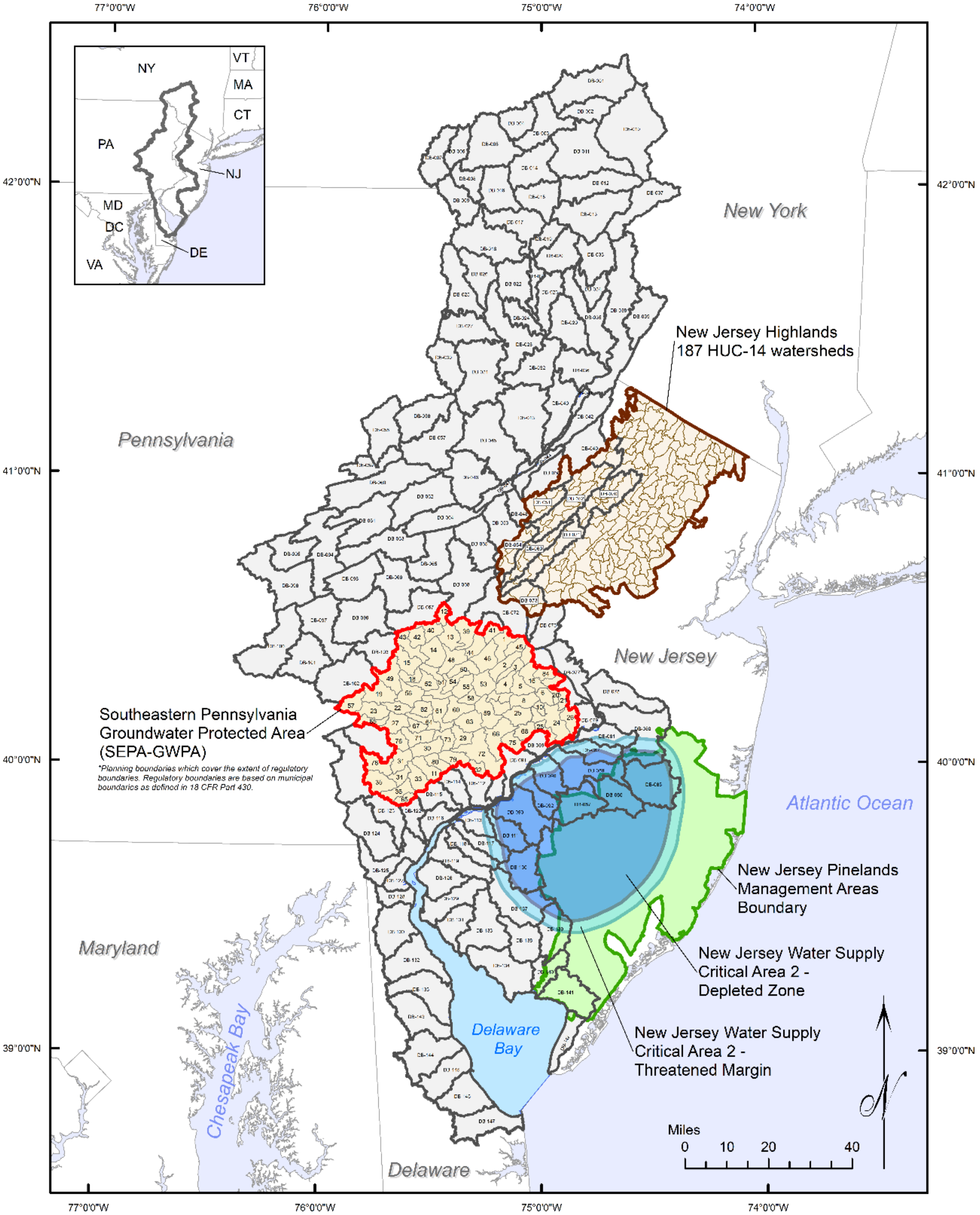


Figure 2: *A map of the groundwater management and special planning areas in the Delaware River Basin, overlying the 147 subbasins defined in (Sloto & Buxton, 2006).*

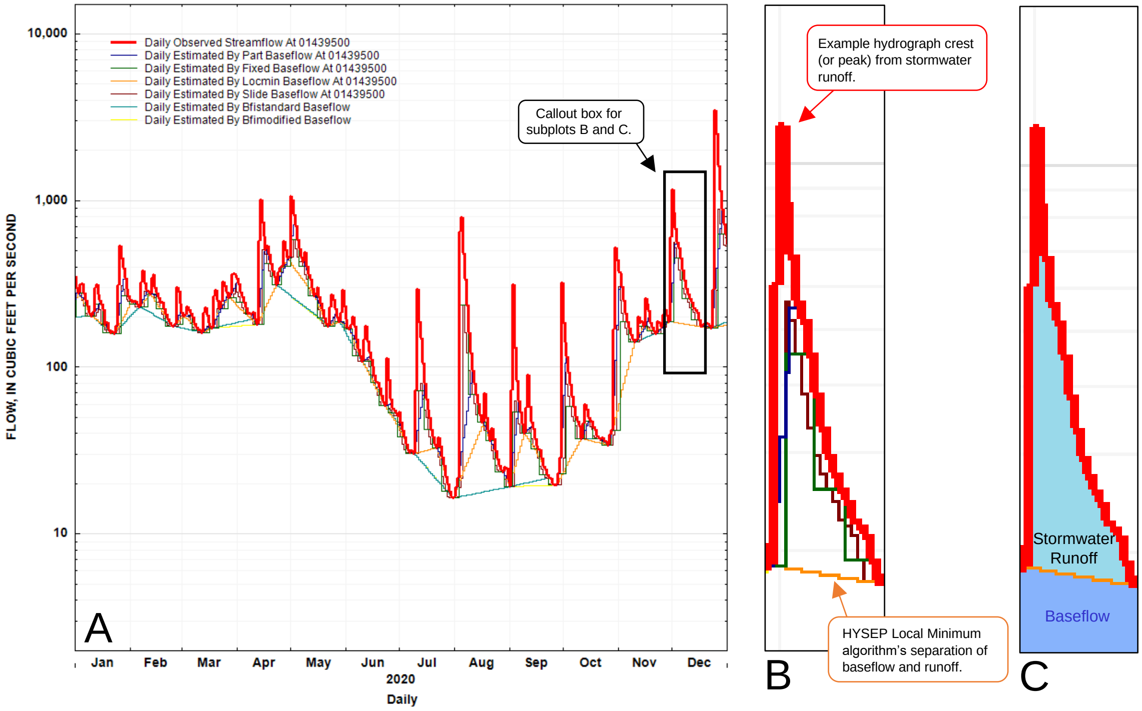


__Figure 3:__ An example stream hydrograph for USGS Site Number 01439500 (Bush Kill at Shoemakers, PA) for 2020. The data were analyzed using six different methods from the USGS Groundwater Toolbox 1.3.3 software to separate the hydrograph between stormwater and baseflow components (Barlow et al., 2015).

2. BACKGROUND

2.1. Baseflow recurrence intervals

An important concept referenced throughout this study is a "baseflow recurrence interval". To better understand this term (and terms which stem from this concept), it is helpful to discuss three concepts in a specific order, as follows.

1. **Baseflow**: Baseflow is the natural groundwater flow to a receiving stream from an aquifer, unimpacted by natural runoff (i.e., rain) or anthropogenic effects (e.g., groundwater pumping or surface water discharges). Figure 3A shows that the U. S. Geological Survey (USGS) Groundwater Toolbox 1.3.3 software can run multiple algorithms to "separate" the stream hydrograph (as shown in Figure 3C) into baseflow (below the analysis line) and runoff (between the analysis line and the hydrograph line). Details on the methodologies and assumptions of the USGS Groundwater Toolbox can be found in Barlow et al., 2015. Baseflow is typically presented as the average baseflow over a month or year per unit area of contributing watershed. For example, in 2020 the average annual baseflow for Bush Kill at Shoemakers, PA, (contributing watershed = 117 mi^2) was 164.5 cubic feet per second (CFS), or 0.909 MGD/mi^2, as calculated using the HYSEP-Local Minimum (HYSEP-Locmin) method (developed by (Sloto & Crouse, 1996; White & Sloto, 1990)). Annual average baseflow data for this gaging station over the period of record (1909-2020; 112 annual records) is provided for reference in Figure 4A.

2. **Flow probability and frequency**: Considering the same USGS Site Number 01439500 (Bush Kill at Shoemakers, PA) which has 112 years of data at the time of this study, a histogram of annual average baseflow provides a general idea of how the data are distributed (Figure 4B). A theoretical

distribution, called a "probability density function", describes the relationship between a variable (such as streamflow) and the probability of occurrence. The area under the probability distribution function represents the sum of all probabilities, and therefore must equal one (Riggs, 1968a). There are many forms of probability distributions historically used in hydrology, such as the Normal, Log-Normal, Gumbel, Pearson Type III, Gamma, and Weibull distributions (Matalas, 1963; Ouarda et al., 2008; Riggs, 1968b). In the example shown in Figure 4B, a Log-Normal distribution is observed to fit the data reasonably well and is plotted on a secondary axis to overlay the histogram.

A more commonly used statistical tool that complements the probability density function is a "cumulative density function", which in hydrology is often referred to as a "flow frequency curve" (Riggs, 1968b). The cumulative density function directly quantifies the relationship between a variable and the probability of occurrence. Theoretically, cumulative density functions are defined by summing a probability density function from either the left or right side. Summing the probability density function from the left side yields the probability that a flow will be equal to or less than a particular value (which is the focus in this study). The cumulative density function corresponding to the Log-Normal distribution in Figure 4B is shown in Figure 4C as the orange line.

Often the cumulative density function is empirically estimated given a finite set of data using "plotting position formulas". There are numerous variations of such formulas detailed in *Statistical Methods in Water Resources* (Helsel et al., 2020); however, a preferred plotting position formula with a long history in hydrology is termed the "Weibull plotting position" (Weibull, 1939), shown below:

$$P_i = \frac{i}{n+1}$$

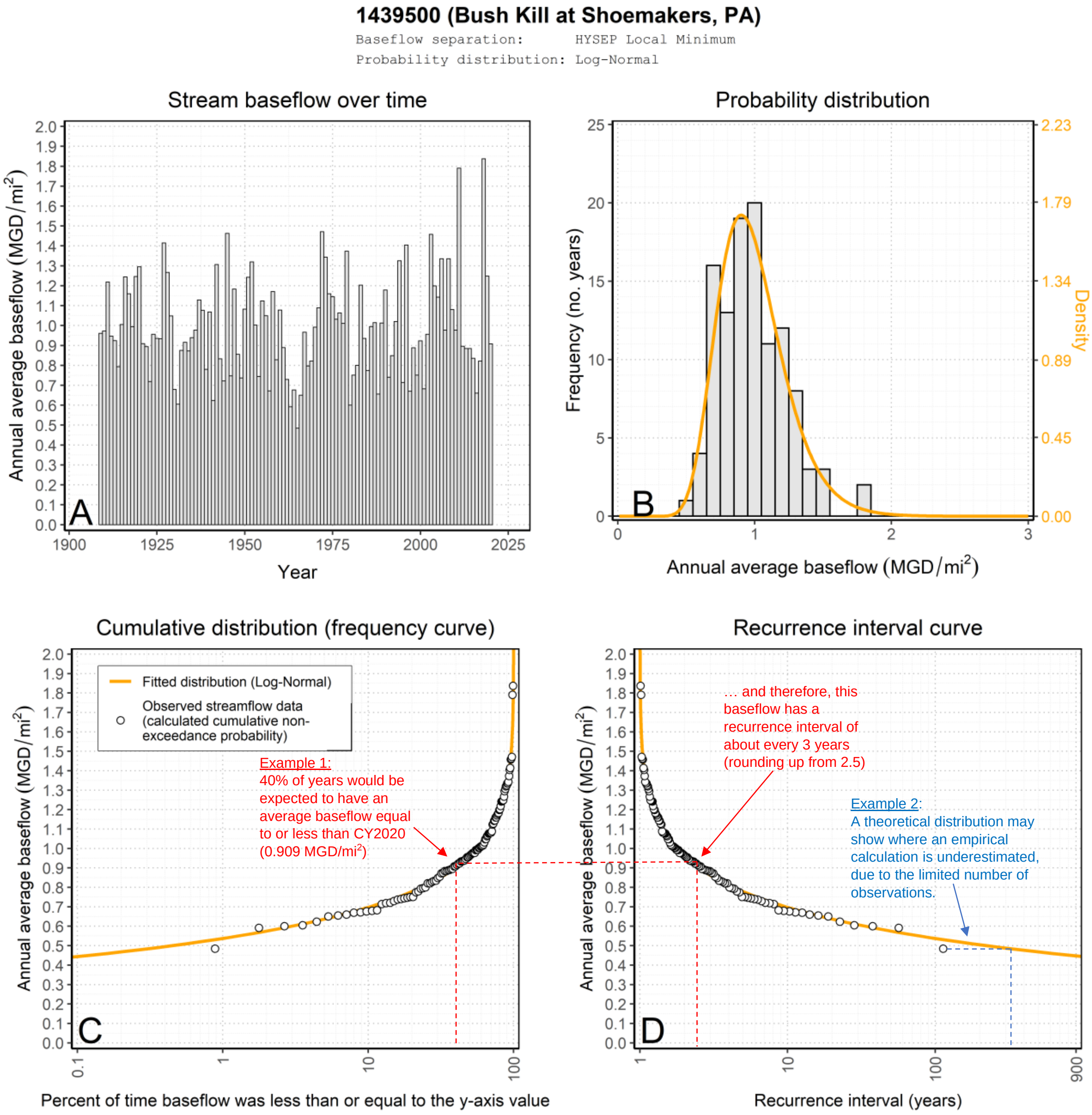
Where is P_i is the calculated probability for the i^{th} ranked observation, given n total observations. Using the 112 data points for USGS Site Number 01439500, the empirical cumulative density probabilities are plotted as white circles on in Figure 4C. In this instance, having a large dataset provides the benefit of empirically estimating an annual average low baseflow with a 1/113 probability (0.9% chance) of occurring in any given year. It is visibly evident that the theoretical Log-Normal distribution matches the empirical data well. Given smaller datasets (e.g., 20 or 30 annual points) the theoretical distribution becomes increasingly important because the empirical probabilities (Weibull plotting position) will only extend to 1/21 (4.8%) or 1/31 (3.2%). In these smaller datasets, the lower probability magnitude of flow may be estimated using the theoretical distribution.

3. **Recurrence Intervals**: A recurrence interval represents the frequency with which a particular a magnitude of a variable (such as streamflow) is expected to occur, and may be calculated as the inverse of the cumulative density function:

$$T = \frac{1}{P}$$

where T is the recurrence interval (in years) for a specific baseflow, and P is the probability that this baseflow value will not be exceeded in a given year. Taking the inverse of both the empirical probabilities and Log-Normal distributions presented in Figure 4C, a recurrence interval curve is presented in Figure 4D. Two examples are shown highlighting how subplots Figure 4C and Figure 4D related to each other.

- The first example considers the average annual baseflow value for calendar year 2020, 0.909 MGD/mi^2 (Figure 3). Based on Figure 4B, average annual stream baseflow will be equal to or less than 0.909 MGD/mi^{2}about 40% of the time. Consequently, the recurrence interval for the 2020 annual average baseflow is about once every three years (rounded to the nearest year from 2.5 years). Therefore, it might be concluded that 2020 is considered a normal year of baseflow for Bush Kill at Shoemakers, PA.



Example 1: 40% of years would be expected to have an average baseflow equal to or less than CY2020 (0.909 MGD/mi²)

… and therefore, this baseflow has a recurrence interval of about every 3 years (rounding up from 2.5)

Example 2: A theoretical distribution may show where an empirical calculation is underestimated, due to the limited number of observations.

Figure 4: *Example analysis of baseflow data.* ***(A)*** *The annual average baseflow (MGD/mi²) over the period of record (1909–2020; 112 annual records).* ***(B)*** *A histogram of the annual baseflow values from (A), plotted with a fitted Log-Normal probability density function (orange line) scaled on the right y-axis.* ***(C)*** *The cumulative density function (orange line) corresponding to the probability density function in (B), with the empirical cumulative density function probabilities of non-exceedance (white circles) calculated from the Weibull plotting position formula.* ***(D)*** *The inverse of the cumulative density function and empirical probabilities presented in (C), representing the recurrence intervals (in years) of annual average baseflow values.*

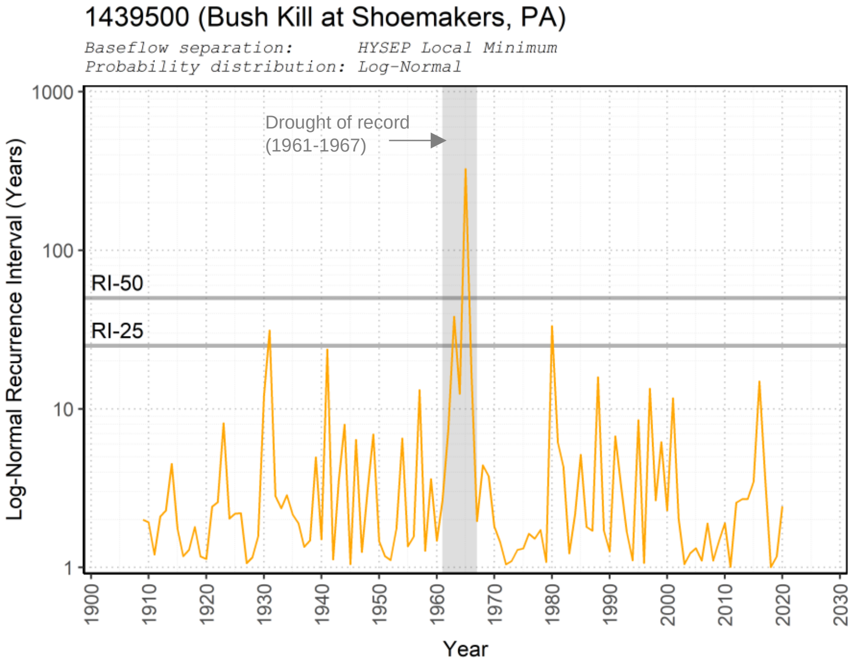


Figure 5: *The recurrence intervals associated with the annual average baseflows calculated using HYSEP-LocMin for USGS Site Number 01439500 (Bush Kill at Shoemakers, PA), based on the fitted Log-Normal distribution in Figure 4.*

> The second example looks at the lowest annual baseflow on record, which occurred during the Drought of Record in 1965, 0.485 MGD/mi^2. Based on a dataset of 112 years, this baseflow value empirically receives a probability of 1/113 (0.9% chance) based on the Weibull plotting position and corresponds to a recurrence interval of 113 years. However, given that the watershed could be characterized by the theoretical Log-Normal distribution, the flow for the year 1965 could be estimated to more accurately be represented by a probability of about 0.3%, corresponding to a recurrence interval of 325 years.

Having reviewed three primary statistical concepts related to baseflow recurrence intervals, it is easier to understand how this information is used in a planning context. Often, studies assess fixed recurrence interval flows as thresholds, for example the 2-year, 5-year, 10-year, 25-year and 50-year recurrence interval flows are among the common choices (Gillespie & Schopp, 1982; Hammond et al., 2022; Schreffler, 1996; Sloto & Buxton, 2006). This approach is based on assumptions that an average annual baseflow which has a 2-year recurrence interval (RI-2) represents relatively normal conditions, having a 50% chance of occurring in a year. On the other hand, an average annual baseflow with a 25-year recurrence interval (RI-25) or 50-year recurrence interval (RI-50) represents increasingly dry conditions, with RI-50 being the most extreme low flow condition considered in this study. This study will continue to use standard nomenclature to refer to a RI-25 baseflow, or a modelling scenario considering RI-25 conditions.

Due to the extended period of record for example gauging station used in this section (USGS Site Number 01439500, Bush Kill at Shoemakers, PA), it is possible to quickly assess the baseflow observed during the 1961–1967 drought of record, which is specified in Section 2.400.1 of the DRBC Water Code to be "*the basis for determination and planning of dependable Basin water supply*" (18 C.F.R. Part 410). The corresponding recurrence interval for each year of annual average baseflow was calculated from the Log-Normal recurrence interval curve (Figure 4D) and plotted in Figure 5. The drought of record is highlighted with a gray background. A distinguishing factor for the drought of record is several consecutive years with low probability baseflows (high recurrence intervals). As was referenced before, flow at this gaging station for the year 1965 could be estimated based on a Log-Normal distribution to represent a 1 in 325-year baseflow (with a 0.3% chance of occurring in a given year).

2.2. Southeastern Pennsylvania Groundwater Protected Area

Development and growth in Southeastern Pennsylvania in the 1970s led to concerns about groundwater depletion in Berks, Bucks, Chester, and Montgomery Counties. Groundwater withdrawals in this region increased by 13 MGD from 1975 to 1980, and a series of conflicts led to legal proceedings in state courts. It was stated in Resolution No. 1980-18 that "*significant portions of the area have experienced total groundwater withdrawals which approached or exceeded the dry period annual recharge rates for the respective formations*". Consequently, depletion threatened the groundwater resources that public water suppliers and private well users depended on, as well as baseflows in perennial streams supporting fish and aquatic life (DRBC, 1980).

Recognizing the importance of regional groundwater, the Commission held several public hearings to gather suggestions about how to proceed and specifically whether regulations should be created to minimize depletion. After the public hearings, in June 1980 it was recommended that the Commission use its authority to "*prevent depletion of groundwater, protect the just and equitable interests and rights of lawful users of the same water source, and balance and reconcile alternative and conflicting uses of limited water resources in the area*" (DRBC, 1980). Section 10.2 of the DRBC Compact delegates power to the Commission to create special protected areas if withdrawals could create a water shortage or prevent certain requirements of the comprehensive plan from being met (PL 87-328, 75 Stat. 688). Section 10.3 delegates power to the Commission to prevent any water users from withdrawing water in exceedance of the Commission's limit unless a permit has been issued (PL 87-328, 75 Stat. 688).

On October 8, 1980, the Commission approved Resolution No. 1980-18, creating a special protected area known as the Southeastern Pennsylvania Groundwater Protected Area (SEPA-GWPA, Figure 6) and enacting groundwater protection regulations in accordance with Section 10.2 of the DRBC compact (DRBC, 1980).

In addition, the Pennsylvania Department of Environmental Protection (PADEP) and DRBC entered into a cooperative agreement on December 22, 1980. The agreement gave the Commission primary responsibility of overseeing the SEPA-GWPA program. Responsibilities included registering all existing groundwater withdrawals and governing all new and existing groundwater withdrawals in accordance with DRBC regulations. The agreement remains in place today with DRBC maintaining primary responsibility to oversee the SEPA-GWPA (DRBC & PADEP, 1980).

The geographic extent of the SEPA-GWPA comprises 128 municipalities named in the regulations. The Commission uses 76 subbasins for assessment purposes that completely cover the municipal extent, are defined as watersheds (with an outlet typically at a confluence of surface waters) and have a mean area of 20 mi^2 (with a standard deviation of 8 mi^2). It is important to distinguish that the SEPA-GWPA regulations set forth in Resolution 1980-18 only apply to the 128 named municipalities. The municipalities do not fully cover each subbasin (Figure 6). The purpose of the SEPA-GWPA regulations is to:

(1) Ensure the sustainable management of water resources in the area,
(2) Ensure that withdrawals are consistent with policies under the Commission's Comprehensive plan,
(3) Ensure that all water users have access to water,
(4) Acquire additional resources to plan and manage water resources, and
(5) Encourage water users to adopt conservation practices (DRBC, 1980).

Under the regulations, no user, entity, or supplier should withdraw groundwater at a rate exceeding 10,000 gallons per day without Commission approval. Those who wish to drill or develop new withdrawal wells within the SEPA-GWPA must notify the Executive Director or obtain a protected area permit (DRBC, 1980). In 1986, the SEPA-GWPA regulations were amended to include withdrawal metering, recording, and reporting requirements, improving data quality. In 1998 and 1999, the regulations were amended again to include withdrawal limits for each subbasin (18 C.F.R. Part 430; DRBC, 1999). The regulations set forth by the Commission have resulted in sustainable groundwater withdrawal in almost all SEPA-GWPA subbasins.

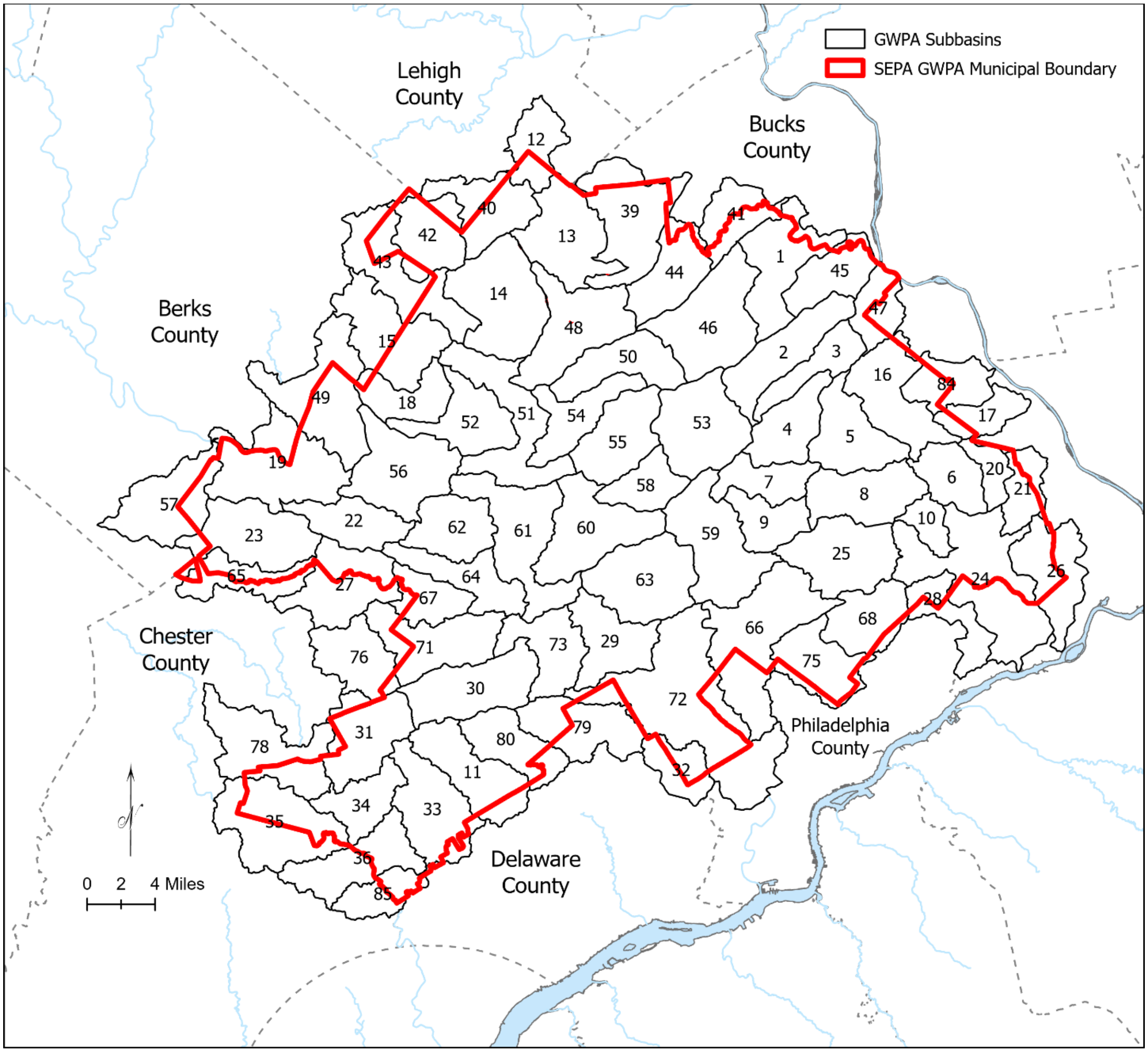


Figure 6: *A map with the boundaries of the Southeastern Pennsylvania Groundwater Protected Area and the boundaries of the municipalities that fall under regulation.*

2.2.1. Withdrawal limits (1998 amendment) (18 C.F.R. Part 430)

In 1996, in cooperation with the DRBC, the USGS developed a pilot method to analyze water use in the Neshaminy Creek Basin that could be applied to other watersheds (Schreffler, 1996). The study sought to organize and summarize all water use data as part of a cooperative agreement with DRBC. Data used in this program included "*public-supply well withdrawals; a combination of industrial, commercial, institutional, and groundwater well withdrawals; spray irrigation systems; a combination of public, industrial, and private surface-water withdrawals*" (Schreffler, 1996).

Four reference streamflow-measurement stations in Southeastern Pennsylvania were used to estimate the baseflow contribution to the Neshaminy Creek Basin from four geological groups (or units). These four stations were selected because the underlying geology largely represents a single geologic type: crystalline rocks, carbonate rocks, the Brunswick Group & Lockatong Formation, or the Stockton Formation. A hydrograph separation program was used to separate surface flow and baseflow components of streamflow using the local minimum method (Sloto & Crouse, 1996). At each station, baseflow values were calculated at 2-, 5-, 10-, 25- and 50-year recurrence using a normal distribution and were used to estimate the yield of each geologic type. Where the period of record was not long enough to calculate the 50-year baseflow, the calculated 2-,5-,10- and 25-year baseflows were extrapolated using a normal distribution.

At the carbonate rocks reference station, the contributing drainage area was reduced because the "*ground-water basin contributing most of the stream-flow passing the streamflow-gaging station is smaller than the surface-water basin*" (Schreffler, 1996). At the Stockton formation reference station, the hydrograph separation program resulted in high baseflow estimates and a different methodology was applied.

After the baseflow recurrence intervals were determined for each geologic type, the values were used to calculate the baseflow recurrence intervals for each of the 14 subbasins comprising the Neshaminy Creek Basin. The percentage of each geologic group in each subbasin was multiplied by the baseflow yield for the respective geologic group at each recurrence interval. The summation of baseflow from the 14 subbasins was taken to represent the total baseflow for the Neshaminy Creek Basin at each recurrence interval (Schreffler, 1996). This calculation follows the generalized equation:

$$Q_{Nesh,RI} = \sum_{i=1}^{14} \sum_{g=1}^{4} A_{i,g} Q_{g,RI}$$

where ($Q_{Nesh,RI}$) is the baseflow of the Neshaminy Creek Basin for a specific recurrence interval, ($Q_{g,RI}$) is the RI-baseflow in MGD/mi^2 for geologic unit *g*, and ($A_{i,g}$) is the area in mi^2 of geologic unit *g* within subbasin *i*. The baseflow for unconsolidated deposits was not calculated due to a lack of data. In the areas where unconsolidated sediments are present, baseflow values for crystalline rocks were used instead.

A second study conducted by the USGS used the same methods to calculate baseflows for the remaining 62 SEPA-GWPA subbasins at 25 and 50 year recurrence intervals (USGS, 1998). The Commission's Groundwater Advisory Committee, predecessor to today's Water Management Advisory Committee (WMAC), recommended amendments to the SEPA-GWPA regulations that "*establish numerical ground water withdrawal limits on a subbasin level*" based on the USGS baseflow frequency analyses (DRBC, 1998). Resolution 98-18 amended the SEPA-GWPA regulations to establish numerical withdrawal limits for subbasins in the Neshaminy Creek Basin and Resolution 99-11 established withdrawal limits for the remaining 62 subbasins. The withdrawal limits are equivalent to the RI-25 baseflow in each subbasin (18 C.F.R. Part 430).

2.3. USGS groundwater studies in the Basin

In 2002, via the passage of Resolution 2002-34, the DRBC contracted with the USGS to conduct several studies of water budgets and baseflow in the Delaware River Basin at a watershed level. The contract furthered the goals of developing a comprehensive water resources plan for the Basin (DRBC, 2002) and improving our understanding of water transport, groundwater storage, and availability throughout the Basin. The approach developed in these studies is the foundation for how the Commission currently assesses Basin-wide groundwater availability.

The first study developed annual watershed budgets based on five model watersheds in the Basin with different geologic settings and varying levels of anthropogenic disturbance. Groundwater withdrawals, groundwater exports, and groundwater returns were calculated for each watershed (Sloto & Buxton, 2005) using a pilot method to analyze components of the annual water budget, including groundwater flow.

A second study, published in 2006, created a methodology for assessing groundwater availability in the Delaware River Basin at a watershed level (Sloto & Buxton, 2006). The study established 147 subbasins within the Delaware River Basin boundary shown in Figure 2, based on a modified hydrologic unit code fifth-level watershed designation (subbasins range in size from 17.9 to 210 mi^2; the average size is 87.4 mi^2). Discussed further in Section 3.1, Sloto & Buxton, 2006 separated the Basin into two areas: (1) subbasins underlain by fractured bedrock, and (2) subbasins underlain by unconsolidated sediments (the Coastal

Plain). Similar methods were developed for each region which allow the *net groundwater withdrawal* (i.e., withdrawal – groundwater recharge) to be compared against the baseflow to a stream, within each subbasin. Calculated as a percentage, the methods act as a screening tool to identify subbasins where net withdrawals are approaching or exceeding expected baseflows to surface water. Subbasins which get screened may warrant additional investigation of groundwater flow dynamics.

To evaluate baseflow from subbasins underlain by fractured rocks, Sloto & Buxton, 2006 used a similar geologic-indexing approach to Schreffler, 1996. The study first generalized 183 mapped fractured-rock geologic units into 14 rock types. Baseflow was then analyzed from historical timeseries of streamflow at USGS gaging stations that (1) had more than 20 years of flow data, (2) primarily drained a single generalized rock type, (3) had a watershed between 10 and 350 mi^2 in size, and (4) did not have any significant regulations or diversions over the 20+ year dataset. These 23 “index stations” were used to characterize typical baseflows per unit area for subbasins underlain by each of the 14 generalized rock types. Hydrographs from each index station were separated into surface runoff and baseflow using the HYSEP algorithm (Sloto & Crouse, 1996), and annual average baseflow values were calculated for each year. Baseflow recurrence interval curves (Figure 4) were then calculated for each index station. If multiple index stations had the same primary underlying rock type, the average of the stations’ baseflow recurrence interval curves was used. Therefore, each of the 14 rock types ultimately have one baseflow value for 2-, 5-, 10-, 25-, and 50-year recurrence intervals. For subbasins which did not have an index station, baseflows at each recurrence interval were calculated using a weighted average based on the percent of each rock type present within the subbasin. Thus, values could be estimated for each subbasin based on its geology, regardless of whether or not the subbasin contained a streamflow gage station (Sloto & Buxton, 2006).

A similar approach was used to evaluate baseflow from unconfined coastal aquifers in NJ and DE. In this case, 25 index stations were identified to represent baseflow for 13 combinations of surficial geology and land use. The HYSEP hydrograph separation program was used to conduct a baseflow recurrence analysis for each index station. In instances where streamflow data were only available from the USGS National Water Information System (NWIS), USGS’s PART streamflow-partitioning program was used instead. If a surficial geology/land use group had more than one index station, an average baseflow frequency curve was created to represent that group. For each group, baseflows for 2-, 5-, 10-, 25-, and 50-year recurrence intervals were generated based on the baseflow frequency curve. These results were applied to 38 subbasins based on their predominant surficial geology and land use (Sloto & Buxton, 2006).

Once recurrence interval baseflows were calculated for all 147 subbasins, the net groundwater withdrawal from each subbasin was compared to the respective baseflow at each recurrence interval (2-, 5-, 10-, 25-, and 50-year) to screen for potential groundwater availability issues. Groundwater withdrawals from confined aquifers underlying the unconsolidated sediments in the Coastal Plain were not considered applicable, as confined aquifers may have more complex dynamics that reach beyond the subbasin boundaries. These baseflow recurrence intervals have served as the basis for past DRBC groundwater availability analyses (Byun et al., 2019; USACE & DRBC, 2008) and are the foundation of groundwater availability projections through 2060 presented in this report.

2.4. Groundwater availability methods review

The methods outlined in the previous sections report (namely those used by Sloto & Buxton, 2006) are one example of how groundwater availability might be assessed. This section highlights several alternate methods used in or near the Delaware River Basin and includes a brief summary for each. It is advisable that readers reference specific primary sources as cited for full details pertaining to each method below.

> **New Jersey: unconfined aquifers and non-reservoir surface water**. The New Jersey Department of Environmental Protection (NJDEP) developed the Stream Low Flow Margin (LFM) Method to assess groundwater availability in New Jersey for water-supply planning (Domber et al., 2013). This water-table-aquifer-based water-budget method includes both water-table (unconfined) aquifers and surface water, which is not regulated as part of a reservoir safe-yield system. The LFM

is defined as the difference between a stream's 7-day, 10-year low flow (7Q10, a typical drought flow) and the September median flow (a typical dry-season flow). NJDEP typically assesses watersheds based on 150 11-digit hydrologic units (HUC11s) (Ellis & Price, 1995), which can be aggregated to represent 20 watershed-management areas (Cohen, 1997).

According to the NJDEP Water Supply Plan (NJDEP, 2017): "*The NJDEP uses 25% of the LFM as a planning threshold of excessive depletive and consumptive water loss. If there is more water loss than this threshold a HUC11 is considered to be stressed. In these areas, no additional depletive and consumptive water loss from the surface water system is recommended.*"

Flow statistics were calculated for periods when it is known that streamflow was not significantly affected by upstream withdrawals or impoundments (Esralew & Baker, 2008). Flow statistics outside of the New Jersey Highlands were adopted from Watson, et al., 2005 if the means of calculation met the study criteria, otherwise they were calculated by the New Jersey Water Science Center (USGS, 2008). Flow statistics for the New Jersey Highlands were adopted from (NJ Highlands, 2008) to the HUC11 scale using an aggregate-flow method; although, the most recent New Jersey Water Supply Plan does not present results for the Highlands area, as the Highlands Council's water resource planning efforts have primacy (NJDEP, 2017).

New Jersey: New Jersey Highlands Region. The New Jersey Highlands Region is an area of approximately 1,342 mi^2, a large portion of which is part of the Upper Delaware watershed (HUC 02040101). As part of the Highland Council's Regional Master Plan, a technical report titled "Water Resources Volume II Water Use and Availability" assessed numerous methods for assessing groundwater availability, prior to making a selection to be used for the New Jersey Highlands (NJ Highlands, 2008). Starting on page 46, the report reviews eight methods: (1) Low Flow Margin of Safety, (2) Aquifer Models, (3) Aquatic Base Flows, (4) Percent of Average Annual Flow (Tennant), (5) Range of Variability (RVA), (6) Hydroecological Integrity Assessment Process, (7) Wetted Perimeter, and (8) R2Cross. Ultimately, the Highland Council chose to use the Low Flow Margin method as the primary tool for each of the 183 HUC-14 subwatersheds within the Highlands Region. The report provides details on how the low flow statistics (median September low flow and 7Q10) were calculated for each HUC14 subwatershed; notably, it details two methods used for the subwatershed which did not have stream gage data: (1) a drainage area ratio method, and (2) a multi-variate regression. As was stated earlier, NJDEP's most recent New Jersey Water Supply Plan does not present results for the Highlands area, as the Highlands Council's water resource planning efforts have primacy (NJDEP, 2017).

Pennsylvania: Water-Analysis Screening Tool (WAST). The Water Resources Planning Act, Act 220 of 2002, required the completion and adoption of a State Water Plan by March 2008. Additionally, it established processes for designating of critical water planning areas (CWPAs) and the preparation and approval of critical area resource plans (CARPs) (27 Pa. Cons. Stat. § 3101, et seq.). CWPAs are defined as areas of the commonwealth where existing or future demands exceed or threaten to exceed the safe yield of available water resources. CARPs are plans developed to address the key problem(s) identified during the CWPA designation process (PADEP, 2009a). In 2003, PADEP entered into an agreement with the USGS Pennsylvania Water Science Center to develop a methodology for assessing statewide water use and availability, in support of identifying CWPAs. A final methodology was published in 2008, termed the Water-Analysis Screening Tool (WAST) (Stuckey, 2008). There are a few notes worth highlighting that pertain to the development of the final methodology:

- It was determined that "*Accurate estimates of existing and future water demands are essential in the screening process to evaluate the current and future adequacy of water supplies"* (PADEP, 2009a). Therefore, PADEP, USGS and DRBC (with assistance from the firm Camp Dresser & McKee (CDM)) developed methodologies to supplement reported withdrawal data, as well as project current withdrawals to the year 2030 (CDM & DRBC, 2005). The report was published as Appendix I to the State Water Plan and included a pilot study of the forecasting methodology applied to the Lehigh River Basin.

- A means to estimate streamflow characteristics of small watersheds (≤300 mi^2) was addressed in a USGS publication, "*Low-Flow, Base-Flow, and Mean-Flow Regression Equations for Pennsylvania Streams*" (Stuckey, 2006), which divides the state into five regions and provides regression equations for each parameters (i.e., low-flow, base-flow and mean-flow) based on multiple variables (e.g., climatological, geological, hydrological, and physiographical basin characteristics).
- Pilot studies were performed on the Wissahickon Creek and Codorus Creek watersheds using the WAST methodology as the initial screening tool for identifying CWPAs. These pilot studies revealed that "*having accurate and complete water withdrawal, discharge and locational data was crucial"*, and therefore *"two levels of data checks and corrections were identified as being necessary prior to conducting a statewide screening with WAST*" (PADEP, 2009a). Therefore, 22 watersheds were selected for focused effort defining procedures, determining effort levels necessary for checking and correcting data, and defining preliminary WAST results. Changes in input data to the WAST were noted to have greatly improved the confidence and accuracy of the screening process.

The final WAST methodology was published in 2008, after it was used in the statewide evaluation (Stuckey, 2008). The WAST method uses two primary inputs to assess a specified watershed area: (1) net withdrawals from the watershed, and (2) initial screening criteria (ISC) for the watershed. The ISC is taken as a percentage of the 7Q10, which was determined for over 10,000 watersheds across Pennsylvania (generally larger than 15 mi^2). The low flow statistics were calculated using the regression equations provided in (Stuckey, 2006). During fall 2007, PADEP ran the WAST model statewide and screened out 90% of watersheds, shifting the focus of attention to the remaining 10% for further data verification and evaluation of mitigation effects. Regional sub-committees reviewed the results and created a shortlist of thirty-two watersheds "*for which DEP and its technical partners would conduct a yet higher level of data verification and analyze potential mitigating factors such as reservoirs, pass-by flows and conservation releases*" (PADEP, 2009a). Among these thirty-two, six are located in the Delaware River Basin:

- Brodhead Creek
- Neshaminy Creek
- West Branch Brandywine Creek
- Little Lehigh Creek
- Macoby Creek
- Hay Creek

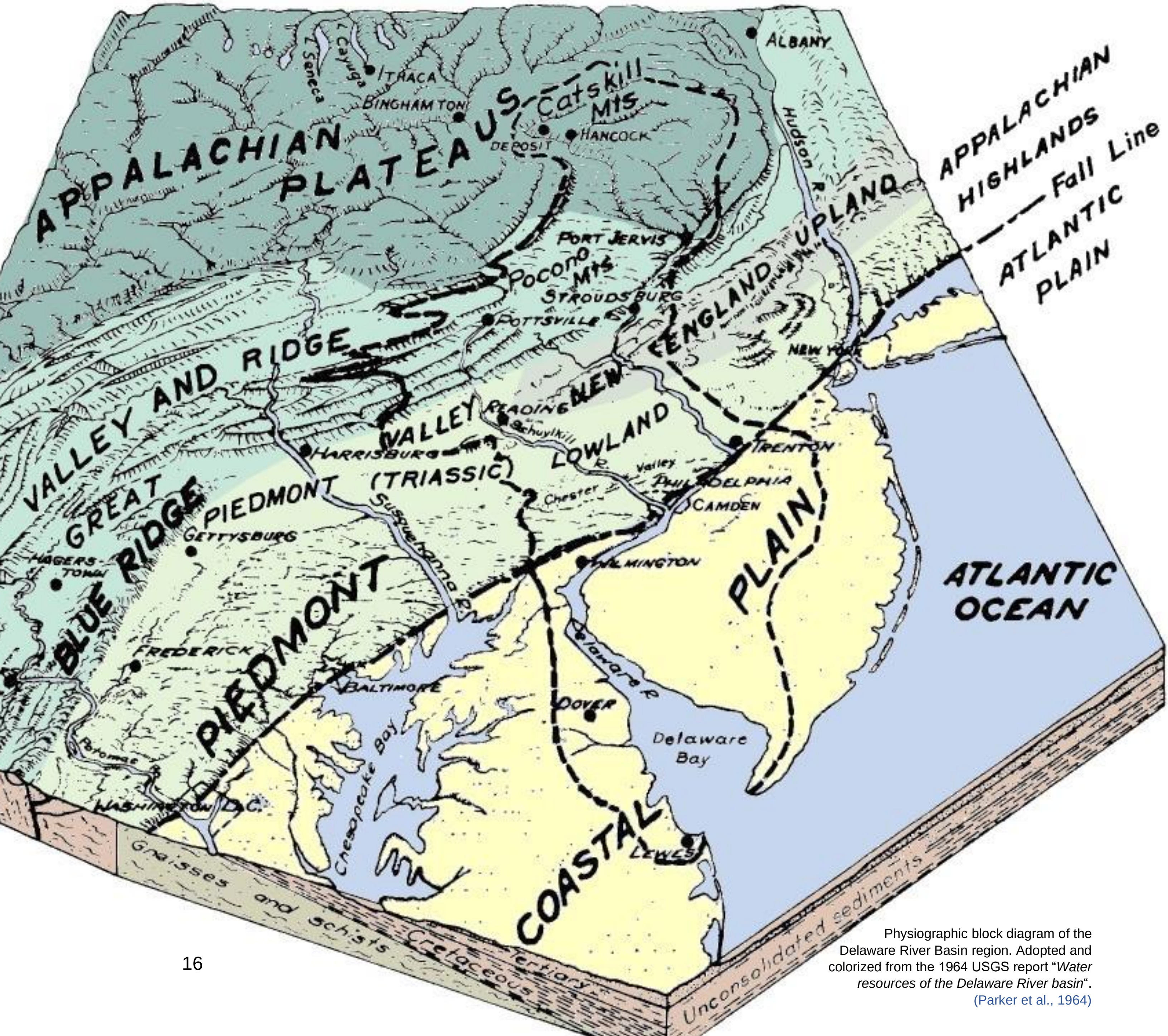
The Wissahickon Creek was not included in the list of six watersheds for further investigation; however, development of a "*Special Area Management Plan*" (SAMP) was initiated in March 2007 to pilot the draft CARP guidelines. The Upper Wissahickon SAMP was ultimately published in 2008 (DRBC & MCPC, 2008). Three of the six watersheds on the shortlist were recommended by the Technical Subcommittee of the Statewide Water Resources for CWPA designation (Brodhead Creek watershed, Little Lehigh Creek watershed, and parts of the Neshaminy Creek watershed), accompanied by detailed reports of supporting documentation (PADEP, 2009b, 2009c, 2009d). None of the three was approved for CWPA designation; rather, the Brodhead Creek and Little Lehigh Creek watersheds were placed on the special watch list, and the Neshaminy Creek was not approved (PADEP, 2010).

New York: Aquifer Delineations. While this is not technically a screening tool for groundwater availability, the delineation of Primary Aquifers and Principal Aquifers in New York is worth noting here. Beginning in 1980 and running through the current day, the USGS has partnered with NYSDEC and other agencies to produce nearly 70 detailed hydrogeologic map reports for selected aquifers throughout New York State, as a scale of 1:24,000 (NYSDEC, 2022). Aquifers of focus are defined in (NYSDEC, 1990) as:

- *Primary Aquifers*: Highly productive aquifers presently being utilized as sources of water supply by major municipal water supply systems.
- *Principal Aquifers*: Aquifers known to be highly productive or whose geology suggests abundant potential water supply, but which are not intensively used as sources of water supply by major municipal systems at the present time.

Susquehanna River Basin Commission (SRBC). SRBC prepared a Groundwater Management Plan to address existing and anticipated groundwater issues in the Susquehanna River Basin (Ballaron et al., 2005). A primary focus was the identification of several Potentially Stressed Areas (PSAs) where groundwater use could approach or has exceeded the average annual baseflow (recharge) available in the "local" watershed during a 1-in-10-year drought. It was stated in the report that "*selection of the 1-in-10-year drought recharge standard strikes a balance among resource conservation, environmental needs, regulatory restriction of growth and development, and the need for adequate and often expensive constructed water storage facilities.*"

An example of this method of evaluation was presented in a study of two groundwater basins in northern Lancaster County: the Manheim-Lititz and the Ephrata Area basins (Edwards & Pody, 2005). This study used average annual (1-in-2-year) recharge rates for specific hydrogeologic units, determined as part of a modelling effort for a 626 mi^2 portion of the Lower Susquehanna River Basin in Lancaster and Berks Counties (Gerhart & Lazorchick, 1984). In that study, hydrograph baseflow separations analyses for six gaging stations (using methodology from Linsley et al., 1949) were used to estimate baseflow in twenty-two hydrogeologic units as a percentage of precipitation; once incorporated into the model of the Lower Susquehanna River Basin, recharge values were normalized for each hydrogeologic unit in MGD/mi^2. Edwards & Pody, 2005 then adjusted these 1-in-2-year values by a correction factor obtained by comparing the 1-in-2-year value for the Conestoga River at Lancaster (station # 01576500 Gerhart & Lazorchick, 1984) to the 1-in-2-year value for the same station reported in White & Sloto, 1990, who made use of three algorithms present in HYSEP. Similar factors were used to convert the Gerhart & Lazorchick, 1984 hydrogeologic unit 1-in-2-year values into 1-in-10-year and 1-in-25 year values. Edwards & Pody, 2005 then apply the corrected baseflow values for each hydrogeologic unit to the Manheim-Lititz and the Ephrata Area basins based on the area of hydrogeologic unit within each basin.



Physiographic block diagram of the Delaware River Basin region. Adopted and colorized from the 1964 USGS report "*Water resources of the Delaware River basin*". (Parker et al., 1964)

3. HYDROLOGIC SETTING

3.1. Basin geology

Physiography is "*a description of the surface features of the Earth, as bodies of air, water and land*" (Powell, 1895). Similar to geomorphology, physiography is more descriptive while geomorphology is a more interpretive study of landforms. Regions within the United States have been categorized into physiographic divisions, provinces, and sections that are "*similar in geologic structure and climate and which have consequently had a unified geomorphic history*" (Gary et al., 1972).

The Delaware River Basin is comprised of two physiographic divisions: (1) the Appalachian Highlands, which is comprised of four physiographic provinces, and (2) the Atlantic Coastal Plain, which has a single physiographic province within the Basin. In turn, the five physiographic provinces are comprised of thirteen physiographic sections (Figure 7). These physiographic sections vary considerably in topography, geology, and hydrology, which create characteristic land development patterns in each section (Fischer et al., 2004). Extending beyond land use patterns, this concept further influences developing trends in water use and withdrawal. When considering groundwater withdrawals specifically, geology becomes a primary focus.

Regarding the twelve physiographic sections underlain by fractured bedrock, Sloto & Buxton, 2006 generalized 183 mapped fractured-rock geologic units into 14 rock types, presented in Figure 8. This generalized lithology was the foundation for estimating groundwater availability, and Table 1 shows their descriptions.

The Coastal Plain was considered separately because the underlying lithology consists of largely unconsolidated sediments that have different hydrologic properties than fractured bedrock. As summarized in Section 2.3, Sloto & Buxton, 2006 reference surficial geology and land use to develop baseflows at defined recurrence intervals. They note that 81% of the New Jersey Coastal Plain within the Basin is comprised of five predominant surficial geologies, descriptions of which are reproduced in Table 2. The surficial geology of Delaware was not available as an electronic vector dataset and was therefore largely not utilized in the analysis of baseflow recurrence intervals. However, the Delaware Coastal Plain within the Basin is comprised of four predominant surficial geologies, summarized in Table 2 with descriptions adapted from (Ramsey, 2007). The regional surficial geology for the Coastal Plain is shown in Figure 9 (data obtained from Delaware Geological Survey [DGS] and NJDEP). An important hydrologic limitation of the methods developed by Sloto & Buxton, 2006 is that "*the watershed approach and equating availability to stream base flow is not suited for estimating confined aquifer groundwater-availability.*" As such, it is worth highlighting the geologic setting of the Coastal Plain.

The Coastal Plain consists of a southward dipping and thickening wedge of unconsolidated sediments underlain by bedrock and overlain by a veneer of local surficial sediments (dePaul et al., 2009). As shown in Figure 10 (adopted from dePaul et al., 2009), the deposits consist of alternating aquifers and confining layers, ranging from about 50 feet thick near the Delaware River to over 6,500 feet thick near the Atlantic Ocean, and generally striking northeast-southwest and dipping 10–60 ft/mi to the southeast (Zapecza, 1989). An example cross-section was adopted from (Stanford, 2004) in Figure 11 to illustrate how the overlying surficial geology compares to the underlying Coastal Plain formation. Regionally, the surficial geology for the Coastal Plain is shown in Figure 9, with markers to indicate where the cross-sections for Figure 10 and Figure 11 are located. Of significant note, generalized surficial geology thickness can be determined by assessing the geologic descriptions provided in NJDEP, 2007; this assessment shows that deposit thicknesses are typically less than 50 feet (about 95% of New Jersey Coastal Plain area).

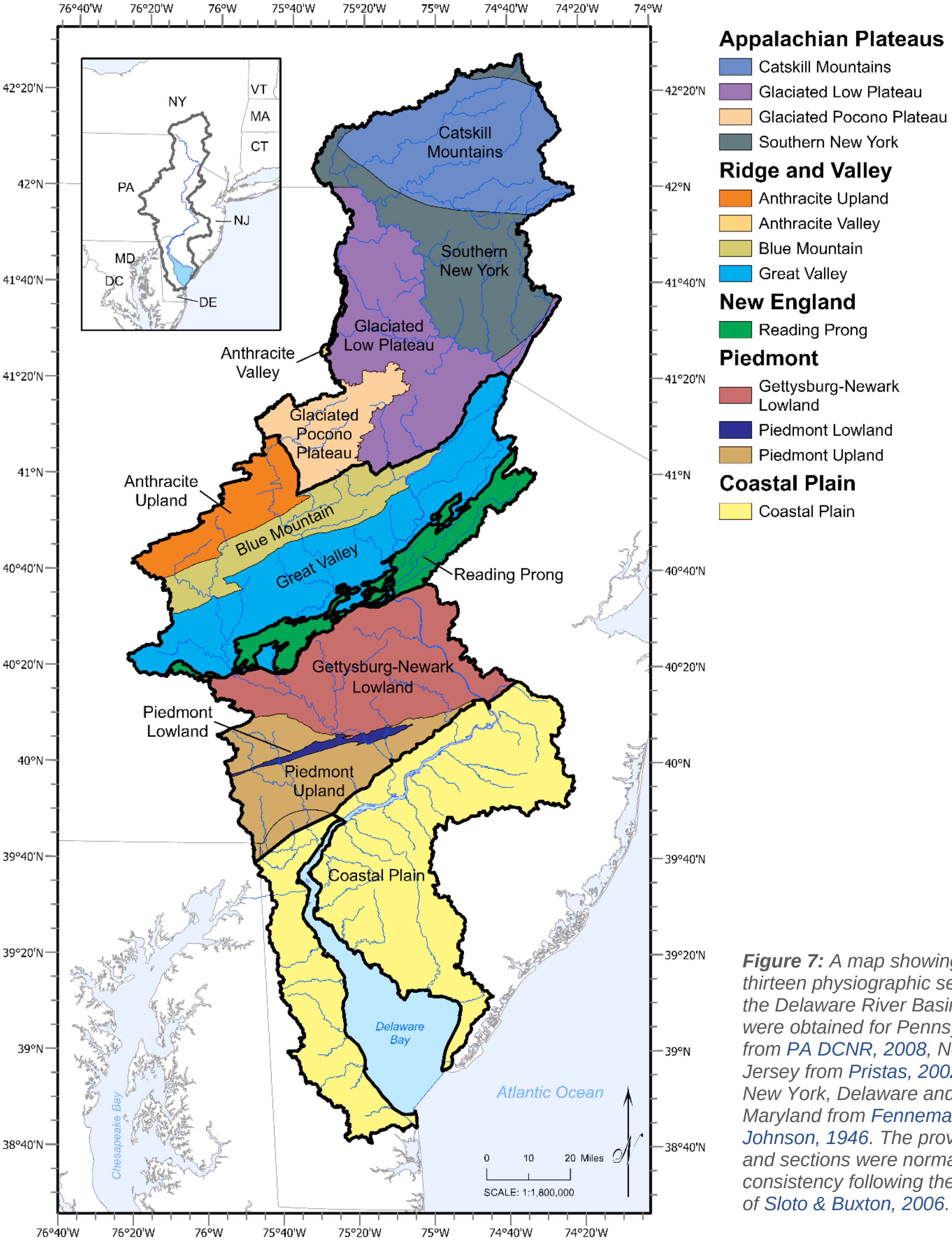
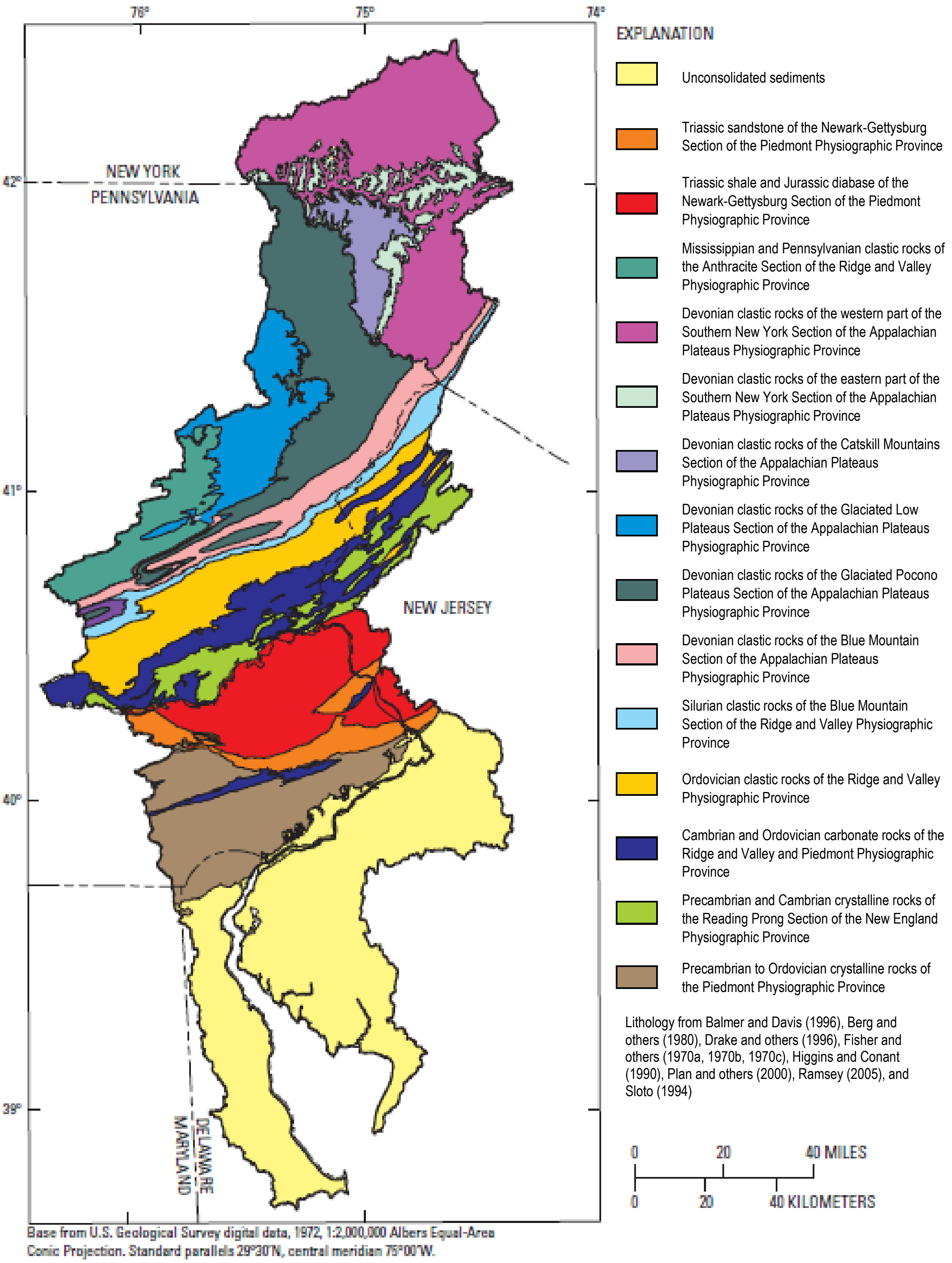


***Figure 7:** A map showing the thirteen physiographic sections in the Delaware River Basin. Data were obtained for Pennsylvania from PA DCNR, 2008, New Jersey from Pristas, 2002, and New York, Delaware and Maryland from Fenneman & Johnson, 1946. The provinces and sections were normalized for consistency following the fashion of Sloto & Buxton, 2006.*



Lithology from Balmer and Davis (1996), Berg and others (1980), Drake and others (1996), Fisher and others (1970a, 1970b, 1970c), Higgins and Conant (1990), Plan and others (2000), Ramsey (2005), and Sloto (1994)

Base from U.S. Geological Survey digital data, 1972, 1:2,000,000 Albers Equal-Area Conic Projection. Standard parallels 29°30'N, central meridian 75°00'W.

Figure 8: *A map showing the generalized lithology of the Delaware River Basin, adopted from Sloto & Buxton, 2006.*

Table 1: *Descriptions of the physiographic sections in the Delaware River Basin that are underlain by fractured bedrock as stated in Sloto & Buxton, 2006.*

Province	Section	Description
Appalachian Plateaus	Catskill Mountains	Underlain by clastic rocks of the Walton, Oneonta, and Gardeau Formations.
	Glaciated Low Plateau Section	Underlain predominantly by Devonian clastic rocks. It is an area of diverse topography consisting of rounded hills and broad to narrow valleys, all of which have been modified by glaciation.
	Glaciated Pocono Plateau	Underlain predominantly by flat-lying, erosion-resistant Devonian clastic rocks that form a broad upland.
	Southern New York	Underlain predominantly by the Honesdale Formation.
Ridge and Valley	Anthracite Upland	Underlain predominantly by Mississippian and Pennsylvanian clastic rocks. It is an upland that has low, linear to rounded hills and is characterized by strip mines, underground mines, and coal-mining waste piles.
	Blue Mountain	Underlain predominantly by Silurian and Devonian clastic rocks that form low linear ridges and shallow valleys.
	Great Valley	Underlain predominantly by Ordovician shale and sandstone of the Martinsburg Formation to the northwest and Cambrian and Ordovician limestones and dolomites to the southeast. It consists of a very broad lowland with gently undulating hills eroded into the shale and sandstone to the northwest and a lower and flatter landscape developed on the carbonate rocks to the southeast.
New England	Reading Prong	Underlain predominantly by Precambrian to early Cambrian crystalline rocks. These rocks form circular to linear, rounded low hills or ridges that project upward in contrast to the surrounding lowlands.
Piedmont	Gettysburg-Newark Lowland	Underlain predominantly by Triassic clastic rocks (primarily sandstone and shale) and intrusive Jurassic diabase. The sedimentary rocks of the Gettysburg-Newark Lowland Section form rolling low hills and valleys. Isolated higher hills are underlain by resistant diabase.
	Piedmont Lowland Section	A long valley (Chester Valley) underlain predominantly by Cambrian and Ordovician carbonate rocks (limestone, dolomite, and marble) of the Chester Valley Sequence.
	Piedmont Upland Section	Underlain predominantly by Precambrian to Ordovician aged metamorphic crystalline rocks (gneiss, schist, and quartzite) that form gently rolling hills and valleys.

3.2. Basin hydrology

The Delaware River has historically been revered as an essential body of water flowing through a picturesque landscape. Even in early non-scientific descriptions, such as the one below, it becomes clear how intertwined the hydrology is with the physical characteristics of the Basin. It is logical then to outline different hydrologic features of the Basin in relation to the physiographic regions and underlying geology.

> *"The sources of the Delaware River are found under the western shadows of the Catskill Mountains in the State of New York… The upper reaches of the Delaware for two hundred or more miles present a continuous series of beautiful vistas… where long and placid intervals between loft promontories are broken by swift rapids as the river gathers volume on its way." (F. H. Taylor, 1895)*

(1) The Appalachian Highlands are predominantly underlain by fractured bedrock and have characteristically high-energy streams and rivers. While these consolidated rocks generally store and transmit much less groundwater than the unconsolidated sediments of the Atlantic Coastal Plain, groundwater is commonly withdrawn from the aquifers. Summarized from Sloto & Buxton, 2006, Figure 13 presents calculated baseflow rates to surface water streams for the 14 generalized lithologies presented in Figure 8. Additionally, a brief hydrologic description of each province is provided below.

Table 2: Descriptions of the predominant surficial geology of the Delaware River Basin Coastal Plain physiographic province. Descriptions for the New Jersey portion were adopted from Sloto & Buxton, 2006. Descriptions for the Delaware portion were adapted from Ramsey, 2007.

Province (State)	Predominant surficial geology	Description
Coastal Plain (New Jersey)	Salt marsh and estuarine deposits (Qmm)	Deposited in salt marshes, estuaries, and tidal channels during the Holocene age sea-level rise and comprised of silt, sand, peat, clay, and minor pebble gravel. The deposits are brown, dark-brown, gray, and black and contain abundant organic matter. The deposits can be as thick as 100 feet.
	Lower (Qtl) and upper (Qtu) stream-terrace deposits	Deposited in the late Pleistocene to late Wisconsinan and middle to late Pleistocene, respectively. Generally, they are sand, pebble gravel, minor silt, and cobble gravel and are varying shades of yellow, red, and brown. The deposits form non-glacial terraces as thick as 20 to 30 feet.
	Cape May Formation (Qcm)	Deposited during two or more sea-level highstands in the Pleistocene as estuarine, beach, and nearshore deposits. The formation is divided into three units based on marine-terrace elevation and ranges in thickness from 20 to 200 feet. The deposits are sand, pebble gravel, minor silt, clay, peat, and cobble gravel and are shades of pale brown, yellow, gray, and white.
	Weathered Coastal Plain formations (Qwcp)	Exposed sand and clay of weathered Coastal Plain bedrock formations. Erosion of these surficial deposits leaves thin, patchy alluvium and colluvium and pebbles.
	Bridgeton Formation (Tb)	Deposited during the late Miocene. It is made up of sand, clayey sand, pebble gravel, and minor cobble gravel (Salisbury and Knapp, 1917). The deposits vary in color, including red, yellow, white, and pale brown, and can be as thick as 40 feet.
Coastal Plain (Delaware)	Marsh deposits (Qm)	Deposited during the Holocene; comprised of structureless to finely laminated, black to dark-gray, organic-rich clayey silt with discontinuous beds of peat and rare shells. Deposits range from 1 to 40 feet thick.
	Scotts Corners Formation (Qsc)	Deposited during the late Pleistocene. The formation is a heterogeneous unit of light gray to brown and light-yellowish-brown; coarse to fine sand, gravelly sand, and pebble gravel with rare discontinuous beds of organic-rich clayey silt, clayey silt, and pebble gravel. Deposits are less than 20 feet thick.
	Lynch Heights Formation (Qlh)	Deposited during the middle Pleistocene. The formation is comprised of clean, white to pale-yellow, well-sorted, fine to coarse sand with scattered very coarse sand to pebble laminae and silty clay laminae overlying light-gray to greenish-gray, compact silty clay with rare laminae of Mulinia shells and shell fragments. Deposits are 10 to 60 feet thick.
	Columbia Formation (Qcl)	Deposited during the early Pleistocene. The formation is comprised of yellowish- to reddish-brown, fine to coarse, slightly silty, feldspathic quartz sand with gravel and some to abundant mica. The formation is typically crossbedded with cross-sets up to 3 feet thick and commonly has beds of gravel (pebbles to cobbles) ranging from several inches to several ft thick. Deposits are typically less than 15 feet thick but can be up to 75 feet thick in channels.

- **Appalachian Plateau**: This province is distinguished by the Catskill and Pocono Mountains, where rivers have carved deep and narrow valleys through folded shales and sandstones. Hydroelectric dams are interspersed throughout the region and New York City has a trio of reservoirs here for water supply. Major hydrologic features include the East and West Branches of the Delaware River (NY), Lackawaxen River (PA), Mongaup River (NY) and Neversink River (NY). All underlying lithology within this province was described as Devonian Clastic Rock; three of the physiographic sections have some of the highest baseflows as shown in Figure 13 (data from Sloto & Buxton, 2006).

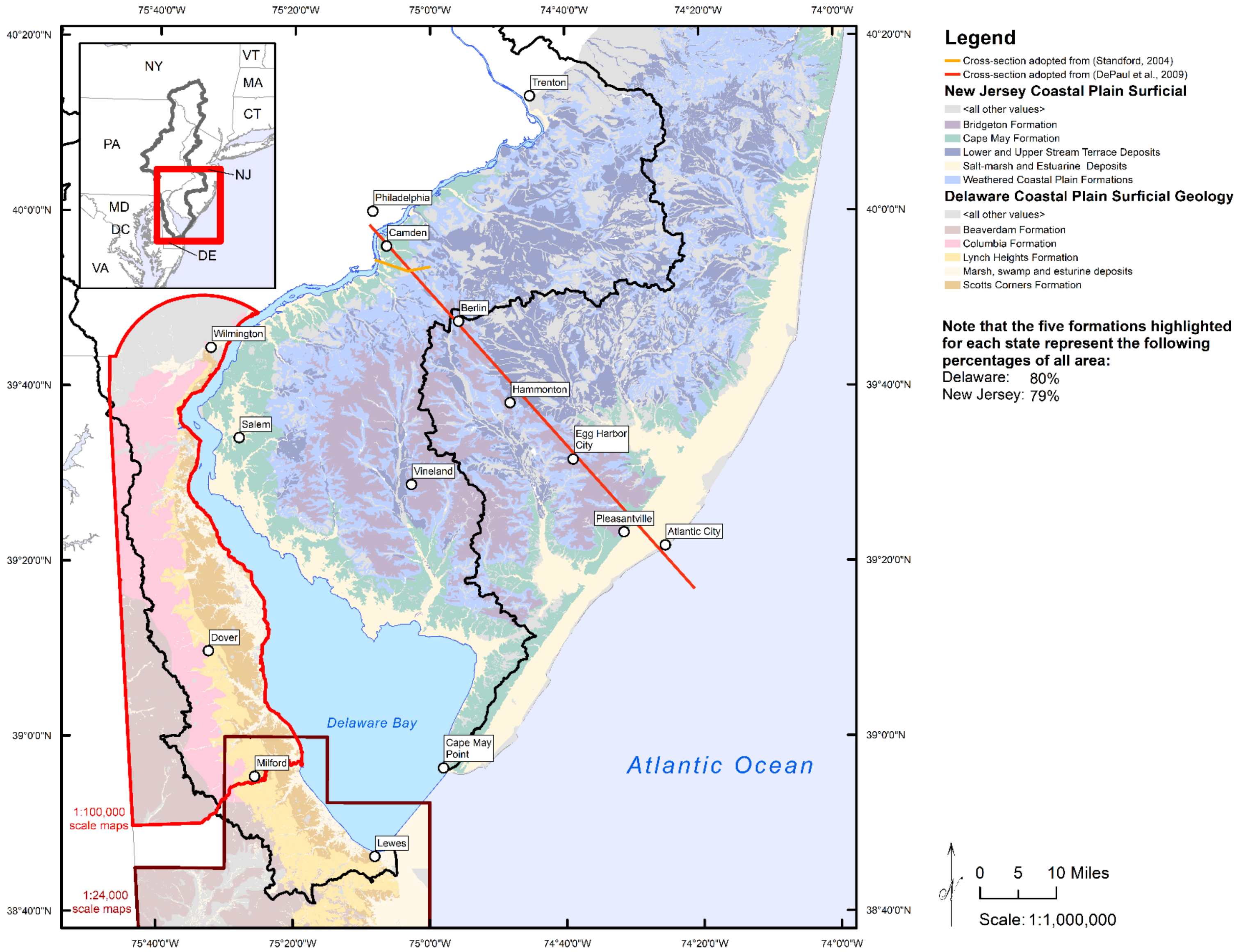


Figure 9: *A map showing the generalized surficial geology of the Coastal Plain of New Jersey (NJDEP, 2007) and Delaware. Data for Delaware is comprised of twelve maps at a 1:24,000 scale (DGS, 1993-2015), and 2 maps at a 1:100,000 scale (DGS, 2005-2007). Surficial deposits are generally Quaternary deposits (Holocene and Pleistocene) and fewer Tertiary deposits (Pliocene and late Miocene). These surficial deposits are overlain upon alternating layers of aquifers and confining units. The New Jersey aquifer cross-section is depicted in Figure 10, with a more local cross-section showing surficial geology thickness in Figure 11. Deposit thicknesses are typically less than 100 feet (about 90% of New Jersey Coastal Plain area) and are generally less than 40 feet (about 70% of New Jersey Coastal Plain area). A cross-section of aquifers underlaying Delaware is depicted in Figure 12.*

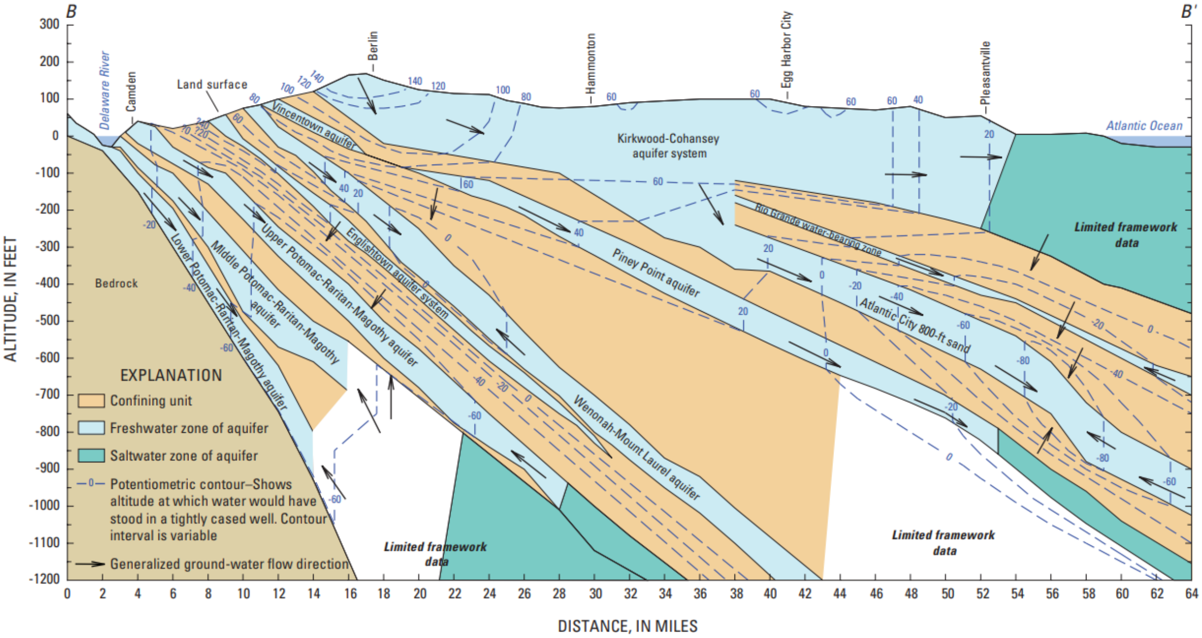


Figure 10: Adopted from dePaul et al., 2009. The relative positions of the aquifers and confining units of the Southern New Jersey Coastal Plain. Potentiometric-surface contours are also indicated, as determined in the referenced study. The aquifers in this diagram are generally underlain by dipping bedrock (shown) and overlain by a veneer of locally occurring Quaternary sediments (as shown in Figure 11). The scale of this cross-section corresponds with the relative extent shown in Figure 9.

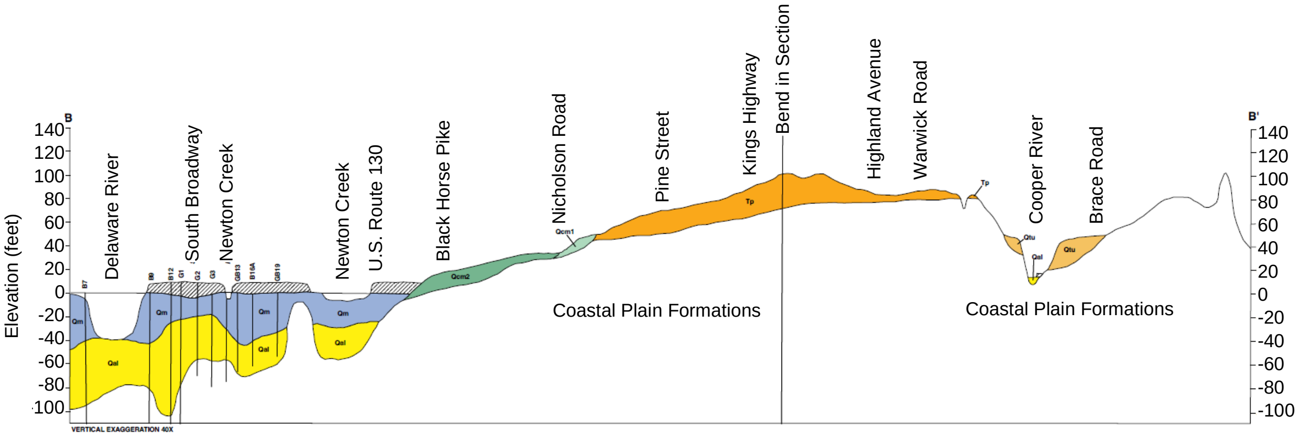


Figure 11: Adopted from Stanford, 2004. A cross-section adopted from the map titled "Surficial Geology of the Camden and Philadelphia Quadrangles, Camden, Gloucester, and Burlington Counties, New Jersey". The scale of this cross-section corresponds with the relative extent shown in Figure 9. The portion of this figure appearing white and labeled as "Coastal Plain formations" are detailed in Figure 10.

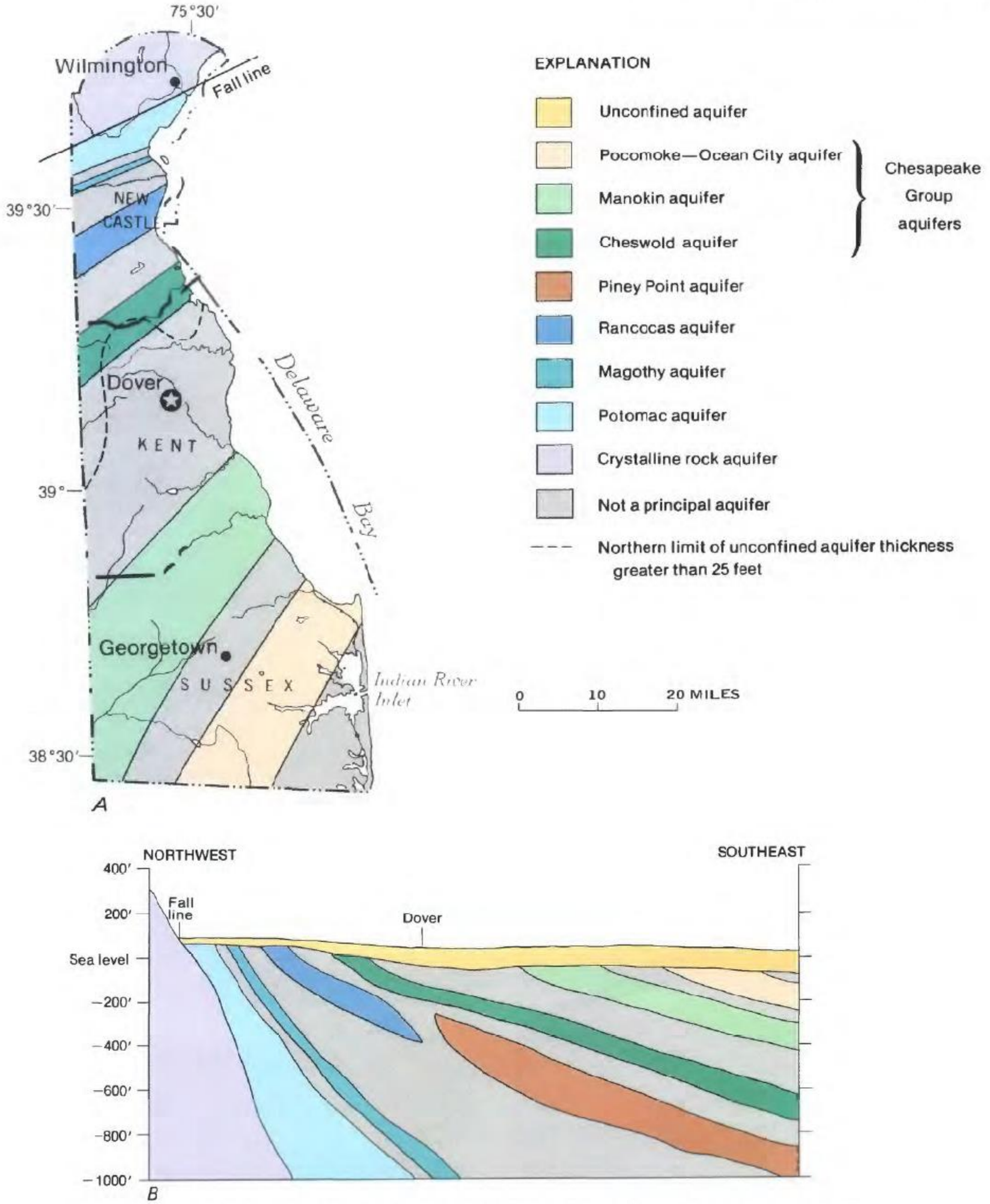


Figure 12: *Adopted from Hodges, 1985. Principal aquifers in Delaware. (A) Geographic distribution. (B) Generalized cross section. Sources for (A) and (B): Cushing et al., 1973; Hodges, 1984; Sundstrom & Pickett, 1971. Note that the surficial geology mapped in Figure 9 corresponds to the "unconfined aquifer" in this figure. More recent mapping of the confined aquifer units is presented in Figure 24, based on Pope et al., 2016 as part of a discussion on the applicability of the Sloto & Buxton, 2006 groundwater availability methodology within the Coastal Plain.*

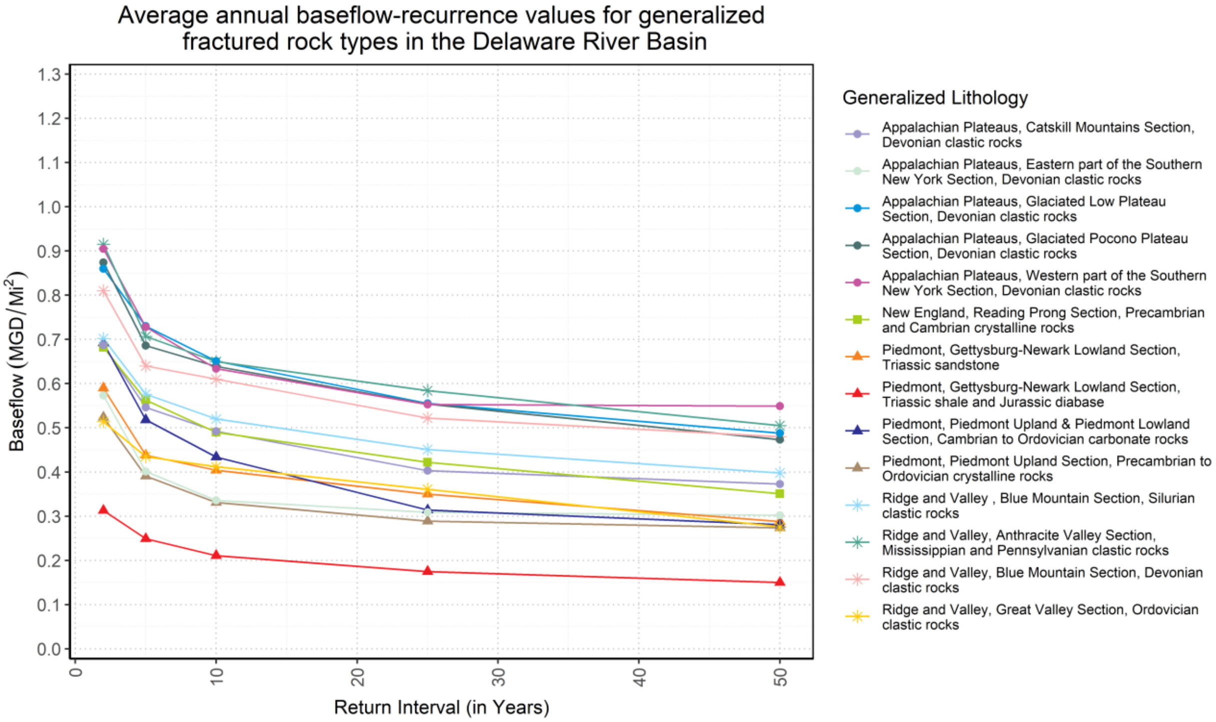


Figure 13: *Average annual baseflow recurrence values for generalized fractured rock types in the Delaware River Basin. These values are summarized from Table 4 presented in Sloto & Buxton, 2006.*

- **Ridge and Valley**: There are characteristic long and narrow forested mountains in this province with developed land and agriculture in the valleys. The Delaware River "enters" this physiographic province by flowing through the unmistakable Delaware Water Gap. The province accounts for most of the Lehigh River watershed, as well as the headwaters of the Schuylkill River watershed. Other notable waterbodies are Flat Brook, Paulins Kill and Pequest River in NJ. The generalized lithology is different for each of the four physiographic sections, covering a broad range of 2-year recurrence interval baseflows from 0.514 MGD (Ordovician clastic rocks) to 0.915 MGD (Mississippian and Pennsylvania clastic rocks) (data from Sloto & Buxton, 2006, shown in Figure 13).
- **New England**: This is an extensively forested region of hills and ridges, drained by a network of steep, rocky streams. Two major water bodies in this province are Pohatcong Creek and Musconetcong River, both in NJ. The only generalized lithology in this physiographic province has recurrence interval baseflows near the middle range of those in the Delaware River Basin (data from Sloto & Buxton, 2006, shown in Figure 13).
- **Piedmont**: There are extensive branching streams throughout this province, flowing between rolling hills. This region is home to the Schuylkill River mainstem, Tohickon Creek (PA), Neshaminy Creek headwaters (PA), and Brandywine Creek headwaters (DE/PA). The generalized lithology is perhaps the most diverse of the four sections, consisting of carbonate and clastic sedimentary bedrocks, as well as crystalline bedrocks. Notably these lithologies are lower yielding than then other physiographic provinces and include the lowest yielding "Triassic shale and Jurassic diabase" lithology (data from Sloto & Buxton, 2006, shown in Figure 13).

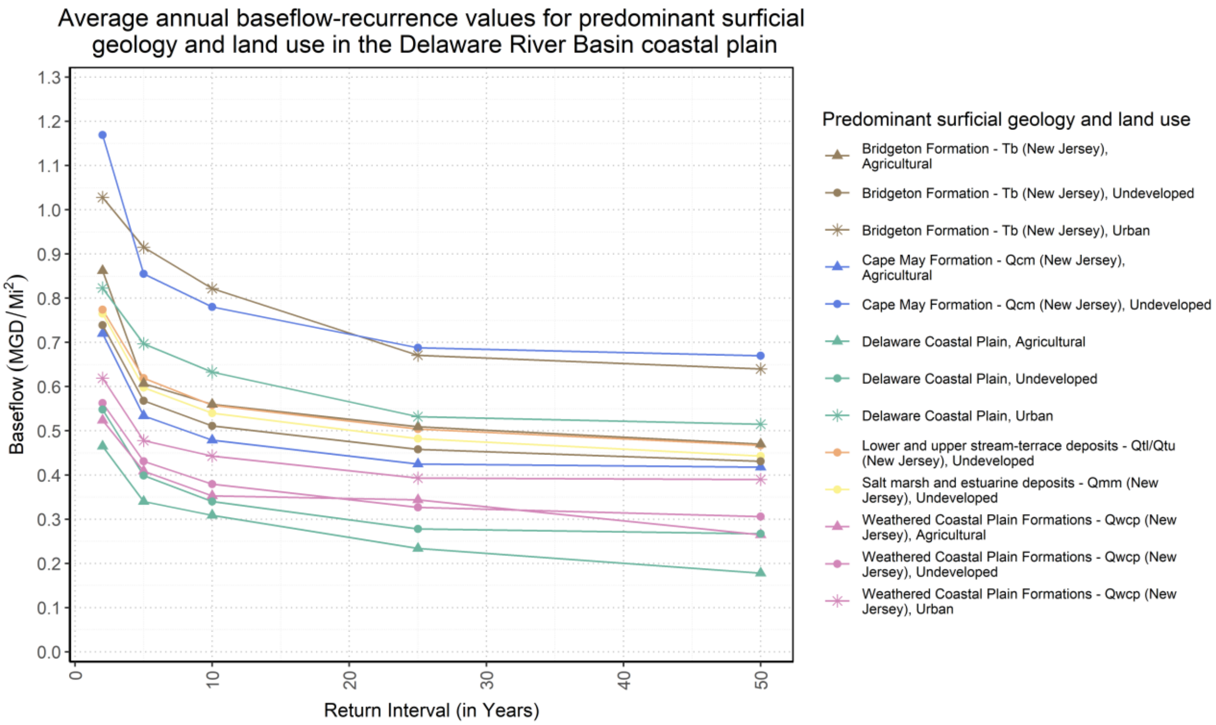


Figure 14: *Average annual baseflow recurrence values for predominant surficial geology and land use in the Delaware River Basin coastal plain. These values are summarized from Table 7 presented in Sloto & Buxton, 2006.*

(2) The Atlantic Coastal Plain, in stark contrast to the fractured rock of the Appalachian Highlands, is a great wedge of unconsolidated sediment. Alternating layers of sand, clay and gravel extend southeast from the fall line, thickening as they slope under Delaware Bay and the Atlantic Ocean. There are many notable surface water features including Delaware Bay, the Chesapeake & Delaware canal, Christina River (DE), St. Jones River (DE), Rancocas Creek (NJ), and Maurice River (NJ). Summarized from Sloto & Buxton, 2006, Figure 14 graphically presents calculated baseflow rates to surface water streams for thirteen generalized surficial geology and land use parameters. On average, the baseflows are higher than the fractured rock counterparts. Notably, the undeveloped Cape May Formation has the highest 2-year recurrence interval baseflow, and the agricultural Delaware Coastal Plain has the lowest.

3.3. Water withdrawals

In general, “water use” may refer to either the withdrawal or end-use of water (e.g., a public water supplier may withdraw water and distribute it for domestic, commercial, or industrial end uses). Many studies have presented snapshots of a single year’s water withdrawals from the Basin (Byun et al., 2019; Hutson et al., 2016; Sloto & Buxton, 2006), and in a few instances time-series of various withdrawal data have been presented for certain sectors (DRBC, 2021). However, a recent DRBC study compiled reported data on water withdrawals from the Basin for 1990–2017 across all withdrawal sectors (Thompson & Pindar, 2021), with projections provided through the year 2060. The data were made available for download and is used as the basis for groundwater withdrawals in this study.

3.3.1. Net withdrawal concept

An important consideration when using the data provided in Thompson & Pindar, 2021 for assessing groundwater availability is the concept of “net” groundwater withdrawal, introduced in Section 2.3 as the difference between groundwater withdrawals and groundwater recharge. Similar to Sloto & Buxton, 2006, this study assumes that infiltration from irrigation and return flows from self-supplied domestic systems via septic fields both contribute local groundwater recharge; recharge from spray-irrigation is not considered. To account for these recharges, only the consumptive portion of the withdrawal is considered to be a "net" withdrawal from the local aquifer; both of these withdrawal sectors use "default" consumptive use rates provided in Thompson & Pindar, 2021.

One additional consideration in this study concerns the mining sector; namely, that mining withdrawals are often associated with dewatering and pumping groundwater directly into a stream. As such only the consumptive portion of mining withdrawals were considered to be net groundwater withdrawals, using a default consumptive use rate provided in Thompson & Pindar, 2021.

3.3.2. Historical net groundwater withdrawals

A map showing net groundwater withdrawals from the Basin for calendar year 2017 is presented in Figure 15, formatted in a similar color scheme as Sloto & Buxton, 2006. The density and magnitude of net groundwater withdrawals varies throughout the Basin. Self-supplied domestic withdrawals were estimated by Thompson & Pindar, 2021 based on the calculated population outside of public water supply service areas, and are represented by planning area.

The data provided by Thompson & Pindar, 2021 were adjusted to reflect net groundwater withdrawals, and historical time series are shown in Figure 16A (Basin-wide) and Figure 16B (SEPA-GWPA). Based on substantial data validation efforts, these time-series are assumed to represent actual (or observed) conditions. Note that Figure 15 represents the spatial distribution of withdrawals which make up the total volume shown in Figure 16 for the year 2017. From these compiled datasets (including data not shown), multiple conclusions may be drawn:

1. Historically, average withdrawals in the Delaware River Basin are 5.4% groundwater and 94.6% surface water. In 2017 they were 6.3% and 93.7%, respectively, which equates to approximately 433 MGD of groundwater and 6,476 MGD of surface water. The groundwater withdrawals adjusted to represent a net withdrawal volume equates to approximately 329 MGD.
2. The proportions of 2017 net groundwater withdrawals were 70.5% public water supply (232 MGD), 11.0% industrial (36 MGD), 8.1% irrigation (27 MGD), 6.3% other (21 MGD), 2.9% self-supplied domestic (9.6 MGD), 0.6% mining (1.9 MGD) and 0.4% thermoelectric (1.8 MGD).
3. Net groundwater withdrawals from the SEPA-GWPA averaged approximately 53 MGD for 1990–1998, and 47 MGD for 2013-2017; net withdrawals have shown a decreasing trend since the late 1990s. The dominant sector of groundwater withdrawal is public water supply.

3.3.3. Projected net groundwater withdrawals

The projection methodology in Thompson & Pindar, 2021 largely relied on a disaggregation methodology, separating water withdrawals into sectors and projecting each sector individually, similar to previous efforts (USACE & DRBC, 2008). A major advancement presented in Thompson & Pindar, 2021 was the further disaggregation of data to the system level and comparison against relevant metadata, such as regulatory approvals. Over 600 withdrawal systems were individually assessed and were determined to account for approximately 99% of the total withdrawal volume from 1990–2017. The remaining 1% was attributed to around 2,400 "unassociated" withdrawal sources assumed to be operated below the Commission's regulatory review thresholds (the data from which were projected with a less intensive review process).

For most withdrawal sectors, projections were estimated by extrapolating historic withdrawal data. For each system, withdrawal data were divided by sourcewater designation (i.e., groundwater or surface water); if applicable, groundwater data were divided by planning region (e.g., 147 subbasins, SEPA- GWPA 76 subbasins) and surface water data were divided by source. Projection equations were then developed for

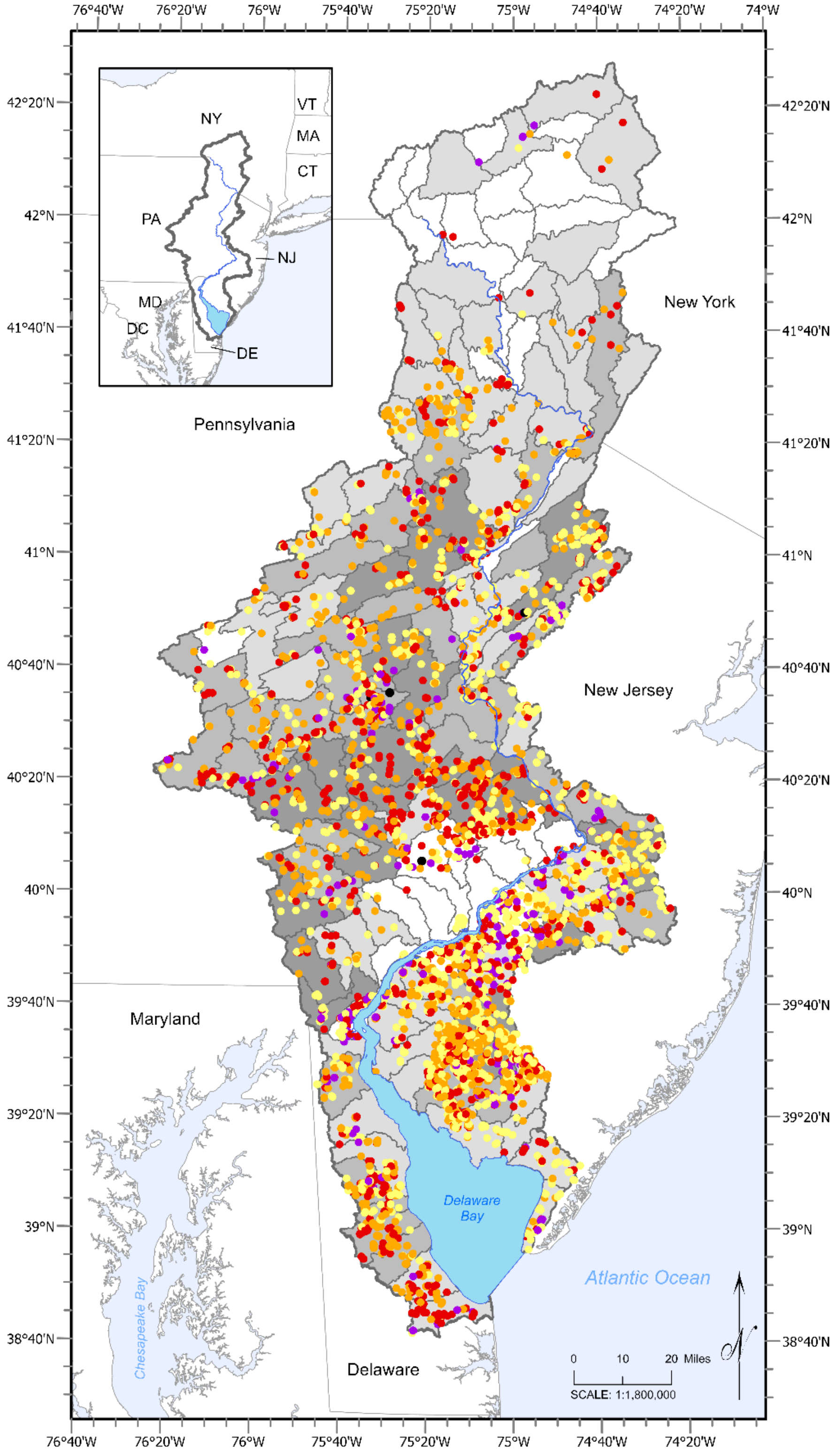


Figure 15: *Map of reported groundwater withdrawals in the Delaware River Basin. Source points are color coded by net withdrawal volume for calendar year 2017. The self-supplied domestic withdrawals estimated by Thompson & Pindar, 2021 are shown by planning area, color coded by net withdrawal volume from each planning area.*

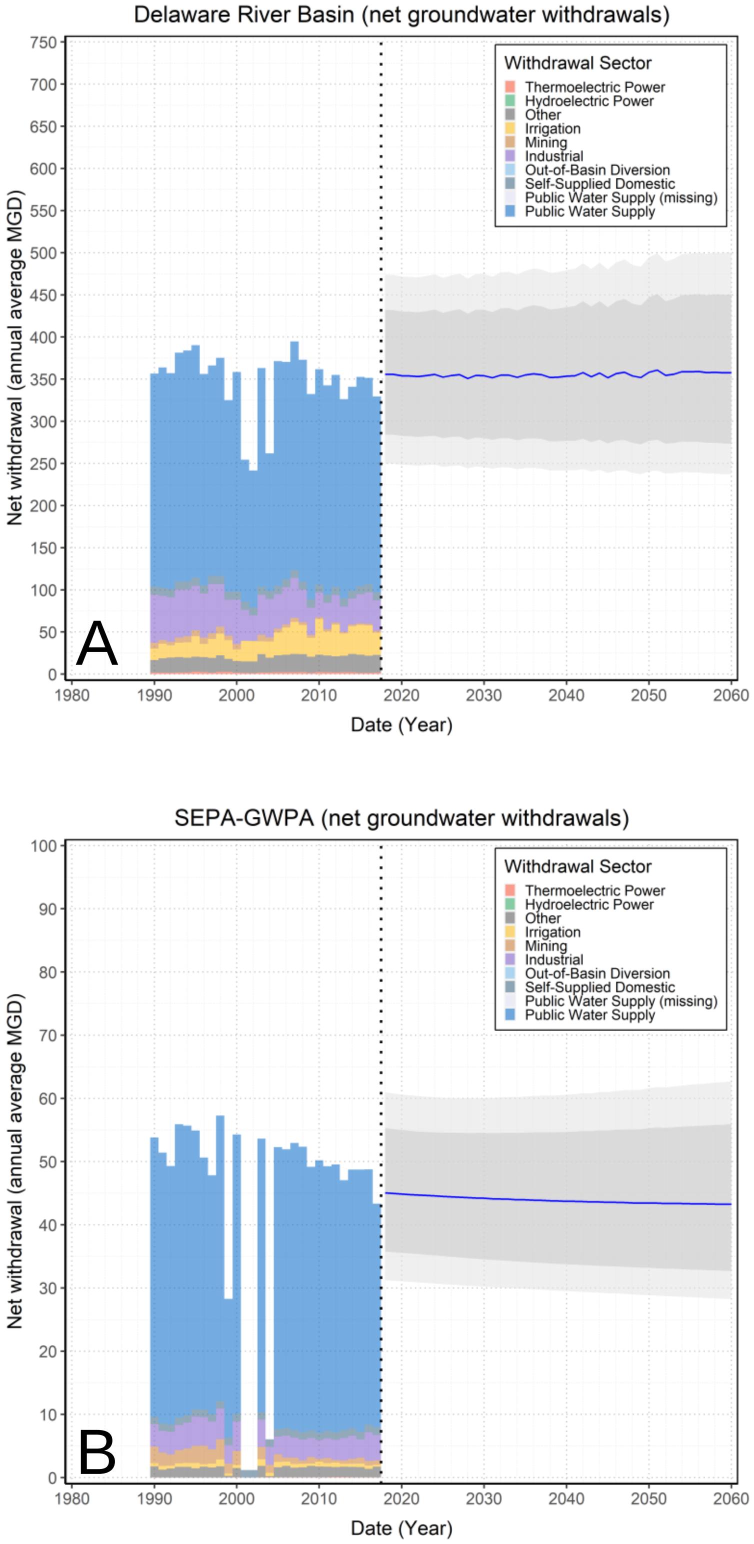


Figure 16: *Historical and projected net groundwater withdrawals in the Delaware River Basin. Note that the y-axis changes between each sub-plot, and that there are public water supply data gaps for the years 1999, 2001, 2002 and 2004.* ***(A)*** *Historical and projected net groundwater withdrawals from the Delaware River Basin, color coded by withdrawal sector.* ***(B)*** *Historical and projected net groundwater withdrawals from the Southeastern Pennsylvania Groundwater Protected Area (SEPA-GWPA), color coded by withdrawal sector.*

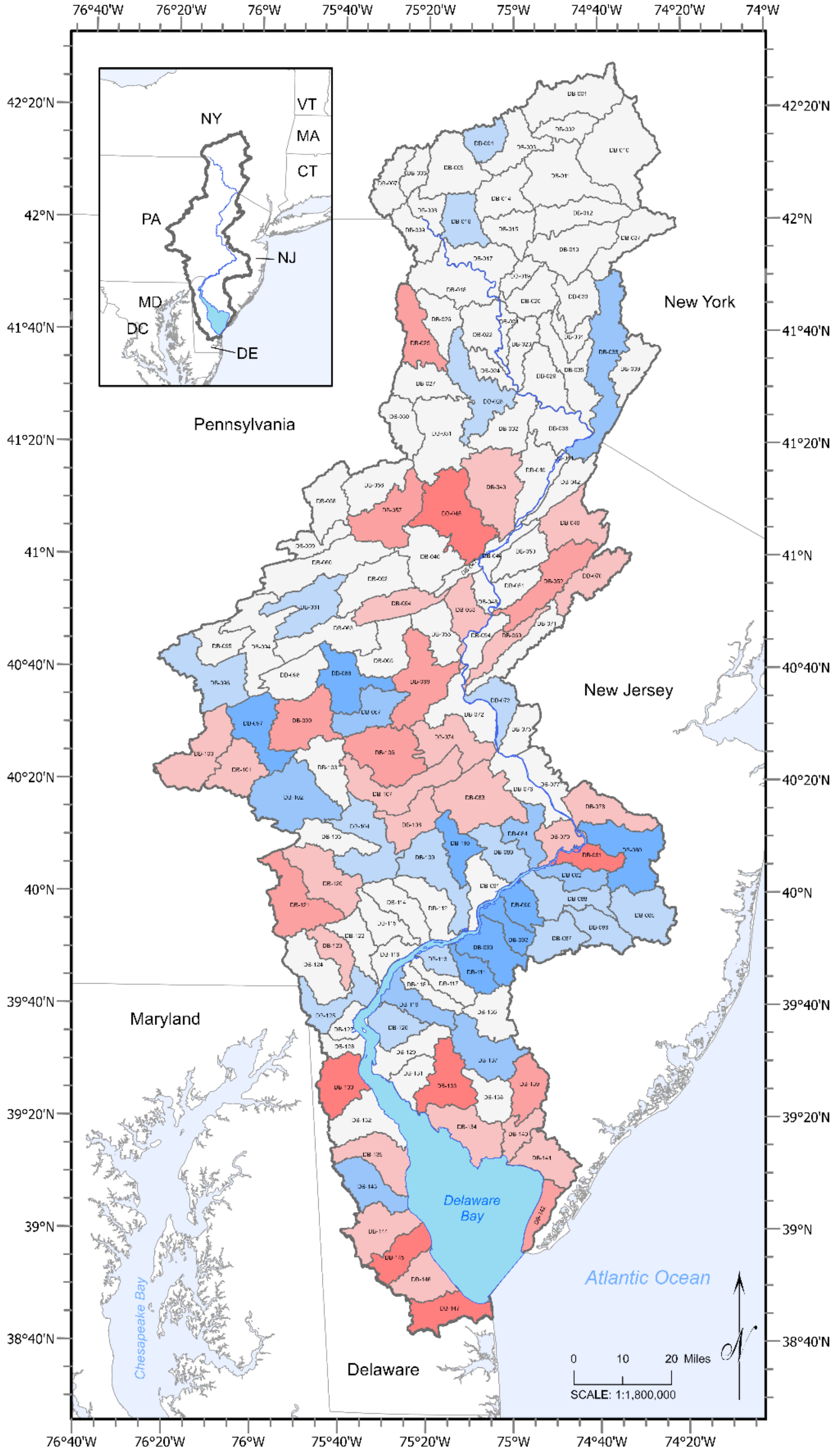
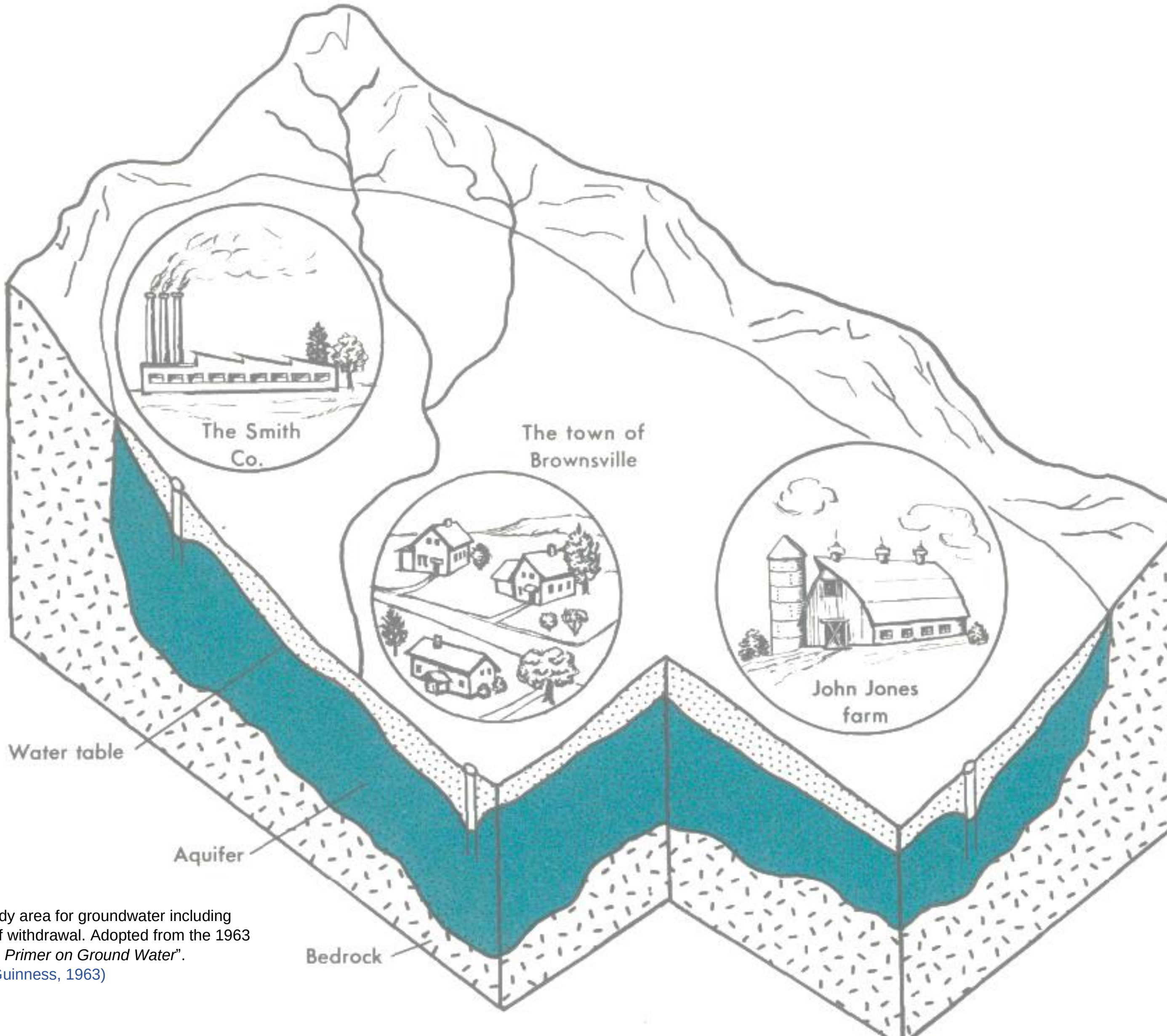


Figure 17: *Map of modelled change in net groundwater withdrawal, from 2018 (projected) through 2060 (projected). Data obtained from Thompson & Pindar, 2021 adjusted for net withdrawals.*

each groundwater planning region and surface water source. Splitting the data below the system level allows projected time-series to be added together in a “bottom-up” approach (Hyndman & Athanasopoulos, 2018) to describe projections of larger regions (e.g., HUC-8 watersheds). This concept was achieved with a report-based methodology with extensive data validation to close gaps in the historical dataset.

In this study, total groundwater withdrawals and projections were adjusted to represent “net” withdrawals, as presented in Figure 16. The projection model for the Basin shown in Figure 16A estimates a net groundwater withdrawal of approximately 356 MGD in 2018 and 358 MGD in 2060, suggesting a constant or equilibrium type projection. However, analysis of the 147 subbasins in Figure 17 shows that 37 are projected to increase withdrawals (totaling +23.5 MGD), 78 are projected to have neutral conditions ($-0.10 < \Delta < 0.10$ MGD), and 32 subbasins are projected to decrease withdrawals (totaling -21.5 MGD). Similar observations were made for the projection of net groundwater withdrawal in the SEPA-GWPA shown in Figure 16B, which estimates approximately 45 MGD in 2018 and 43 MGD in 2060, suggesting a constant or equilibrium type projection. Analysis of the 76 subbasins show that 12 are projected to increase withdrawals (totaling +3.5 MGD), 55 are projected to have neutral conditions ($-0.10 < \Delta < 0.10$ MGD), and 7 subbasins are projected to decrease withdrawals (totaling -5.3 MGD). “Predictive intervals” were calculated based on the quality of projected data (for withdrawals and consumptive use); aggregated 80% and 95% prediction intervals for withdrawals shown in Figure 16.



An example study area for groundwater including three sources of withdrawal. Adopted from the 1963 USGS report “*A Primer on Ground Water*”. (Baldwin & McGuinness, 1963)

4. METHODS

4.1. Data sources

1. **Baseflow data, Basin-wide.** The Basin-wide assessment was performed using the 147 subbasins and estimated baseflows at specified recurrence intervals as defined in Sloto & Buxton, 2006. Baseflows at RI-25 and RI-50 were obtained for subbasins underlain by fractured bedrock and unconsolidated sediments and converted to million gallons per year (MGY).
2. **Baseflow data, SEPA-GWPA.** Two sets of baseflow values were obtained for the SEPA-GWPA from 18 C.F.R. Part 430: (1) a "withdrawal limit" for the net annual groundwater withdrawal from a subbasin, based on the RI-25 average annual baseflow rate, and (2) a net annual groundwater withdrawal threshold defined as 75% of the withdrawal limit, at which a subbasin is deemed "potentially stressed".
3. **Groundwater withdrawal data.** Data on projected groundwater withdrawals were compiled from Thompson & Pindar, 2021, *Water Withdrawal and Consumption Use Estimates for the Delaware River Basin (1990-2017) With Projections through 2060*. The projected groundwater withdrawal rate and the upper 95% predictive interval rate were adjusted in this study to reflect net withdrawals (shown in Figure 16). As was discussed in Section 3.3.1, groundwater withdrawals for self-supplied domestic and irrigation purposes are assumed to have some degree of groundwater recharge, and only the consumptive portion of mining withdrawals are considered net.

4.2. Availability analysis

The projected annual net groundwater withdrawal from each subbasin is presented as a percentage of the corresponding estimated baseflow at 25- and 50-year recurrence intervals; the recurrence interval baseflow values are adopted from (Sloto & Buxton, 2006). These percentages act as a screening tool for planning purposes, such that planning areas with high percentages (indicating potential over-extraction of groundwater) can be flagged for further investigation. The percentage of baseflow withdrawn from each planning area is calculated based on the following equation:

$$\frac{\sum_{s=1}^{N} w_{s,i}}{b_{i,RI}}$$

where $w_{s,i}$ is the net groundwater withdrawal from sector s in subbasin i (in MGY), N is the number of sectors, and $b_{i,RI}$ is the baseflow from subbasin i at recurrence interval RI (in MGY). For example, subbasin DB-001 has an estimated baseflow of 21,161 MGY at a 25-year recurrence interval, and the projected 2020 net groundwater withdrawal rate for all sectors is 236 MGY. Therefore, about 1% of available of groundwater is projected to be used in 2020. This process is conducted for multiple scenarios considering the variables below, creating six sets of results (three for each planning scale). The results are compiled in a series of visualizations and tables which are used as a screening tool to evaluate groundwater availability.

Planning scales: Basin-wide (147 subbasins), SEPA-GWPA (76 subbasins)
Baseflows: 25-year and 50-year recurrence interval flows
Withdrawals: Projected values (2020 and 2060) and the 95% predictive interval (2060)

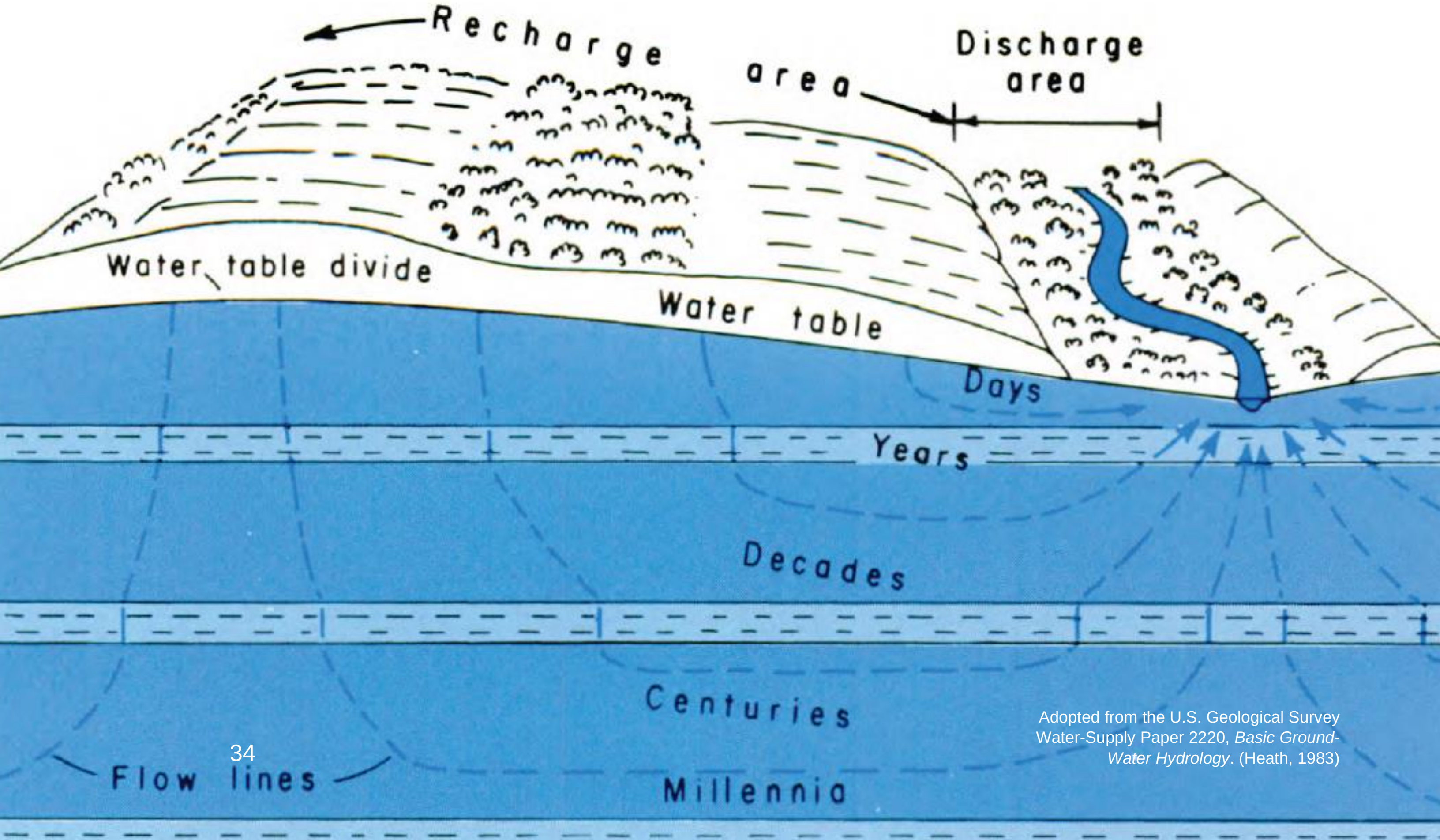
4.3. Data analysis tools

Most analyses were performed in the computing language *R* (R Core Team, 2022). Further data analyses were also performed in Esri's ArcGIS Pro application using various geoprocessing tools (ESRI, 2020).

4.4. Limitations and assumptions

This study largely uses methodologies and data outputs from previous studies. Therefore, the majority of assumptions and limitations are inherently presented in the initial studies and carry through to the present study. Some assumptions and limitations worth highlighting from key reference studies are included in the list below. Additionally, this study makes the assumption that the groundwater withdrawal data from Thompson & Pindar, 2021 can be corrected to reflect net withdrawal, following the discussion outlined in Section 3.3.1.

1. (Schreffler, 1996) *Water-use Analysis Program for the Neshaminy Creek Basin, Bucks and Montgomery Counties, Pennsylvania*
    - Due to a lack of data about the baseflow contributions of unconsolidated deposits in the lower section of the Neshaminy Creek, baseflow values from crystalline rocks were used to determine groundwater contributions to baseflow.
    - At stations where a 50-year record was not available, extrapolation techniques were used to extend the data and linear interpolation was used to calculate some recurrence intervals.
2. (Sloto & Buxton, 2006) *Estimated Ground-Water Availability in the Delaware River Basin, 1997-2000*
    - Each of the 147 subbasins are a closed system and groundwater discharges directly to streams; there is no flow across subbasin boundaries.
    - Groundwater availability in each subbasin is equal to average annual baseflow.
    - The HYSEP program is assumed to adequately separate streamflow hydrographs into baseflow and overland-runoff components. In the Upper Basin, some baseflow determined by HYSEP may be snowmelt which results in overestimates.
    - A common period of record was not used because there was not enough data from each of the index stations to create a 50-year recurrence interval.
    - At stations where a 50-year record was not available, extrapolation techniques were used to extend the data and linear interpolation was used to calculate some recurrence intervals.
    - The watershed approach and equating availability to stream baseflow is not suited for estimating confined-aquifer groundwater availability.
3. (Thompson & Pindar, 2021) *Water Withdrawal and Consumptive Use Estimates for the Delaware River Basin (1990-2017) With Projections Through 2060*
    - Trend extrapolation inherently assumes that the rate of change in water use over the recent past is assumed to continue into the future at the same rate of change.
    - Underlying assumptions of trend extrapolation are that either (a) there is no correlation between time and factors that affect water use, or that (b) time and factors that affect water use are perfectly correlated. This assumption is addressed in the report.
    - Pump capacities are not considered a limiting factor in projections.
    - Negative projected withdrawal values are replaced with zeros as a lower limit.
    - The study does not attempt to forecast the discontinued operation of, or construction of new and existing facilities.
    - The study attempts to project “current trends” of operating withdrawal systems, and therefore does not always use the entire historical dataset in a given projection.
    - Self-supplied domestic withdrawals are assumed to be entirely groundwater, based on a single per-capita rate per state. The self-supplied population is assumed to be the portion of population plotting outside of public water supply service areas.
    - Irrigation projections are related to a regional climate model’s output temperature data, and therefore inherently accepts the assumptions made related to RCP 4.5 and RCP 8.5.



Adopted from the U.S. Geological Survey Water-Supply Paper 2220, *Basic Ground-Water Hydrology*. (Heath, 1983)

5. RESULTS

Results from this screening tool are divided into two subsections: one focusing on Basin-wide availability and another focusing on availability within the SEPA-GWPA. Each subsection contains geospatial and tabular results for 2020 and 2060, with 25-year or 50-year recurrence interval baseflows, using projected net withdrawals or the 95% prediction interval (95%PI) net withdrawal.

The results highlight which subbasins are projected to approach or exceed the estimated available groundwater during a dry year (RI-25 baseflow) or exceptionally dry year (RI-50 baseflow). If projected withdrawals in a subbasin exceed RI-25 or RI-50 baseflow, it does not necessarily indicate persistent groundwater supply issues, given that preceding and/or following years may provide surplus groundwater. For example, DB-067 is expected to use 50–75% of available groundwater during a dry year (RI-25 baseflow), but during a normal year (RI-2 baseflow), the same net withdrawal would comprise a much lower percentage of available groundwater. On the other hand, multiple dry years in a row would present a more dire situation. As was highlighted by the example shown for USGS Site Number 01439500 (Bush Kill at Shoemakers, PA) in Figure 4, the estimated recurrence intervals (based on a Log-Normal distribution) associated with baseflows during the drought of record were: 1 in 38 years (1963), 1 in 12 years (1964), 1 in 325 years (1965), and 1 in 17 years (1966). These considerations are important when interpreting the screening tool results.

5.1. Delaware River Basin

The screening tool at the Basin-wide scale was applied to 121 of the 147 subbasins, excluding some of the Coastal Plain as discussed in Section 5.1.4. The excluded subbasins are grayed out in tables and figures.

5.1.1. 25-year Recurrence interval baseflow

RI-25 baseflow represents a dry year with below-normal baseflow. Figure 19 shows the RI-25 baseflow as it relates to the projected net withdrawal and 95%PI net withdrawal. In the RI-25 baseflow scenario, projected net withdrawals are not expected to use more than 51% of available groundwater in any subbasin in 2020 or 2060. Percent use of available groundwater among projected net withdrawals does not change by more than ±7% between 2020 and 2060. With 95%PI withdrawals, percent use of available groundwater does not change by more than ±10% between 2020 and 2060 (Table 3). Many subbasins use a greater percent of available groundwater (sometimes by ~10%) with 95%PI withdrawals as compared to projected net withdrawals. For example, 95%PI net withdrawals in DB-125 and DB-139 for 2060 fall in the range of 25–50% of available groundwater, whereas the range is 0–25% considering the projected net withdrawals. The withdrawal of available groundwater within DB-054 and DB-067 was 20% higher with 95%PI withdrawals compared to projected withdrawals.

5.1.2. 50-year Recurrence interval baseflow

RI-50 baseflow represents an exceptionally dry year, meaning baseflow is much below normal levels. Figure 20**:** shows RI-50 baseflow as it relates to the projected net withdrawal and 95%PI net withdrawal for all 147 subbasins. With projected net withdrawals, percent use of available groundwater does not change by more than ±8% between 2020 to 2060 (except for DB-145, in which the net groundwater withdrawal is projected to increase from 24% to 37% of available baseflow). With 95%PI net withdrawals, percent use of available groundwater does not change by more than ±14% from 2020 to 2060 (Table 3). In 2060, many subbasins use a greater percentage (sometimes by 10–20%) of available groundwater with 95%PI net withdrawals (right panel of Figure 20**:**) compared to projected net withdrawals (middle panel of Figure 20**:**). With 95%PI net withdrawals, DB-067 is projected to use 79% of available groundwater during an exceptionally dry year, while DB-054 is projected to use 57% (Table 3).

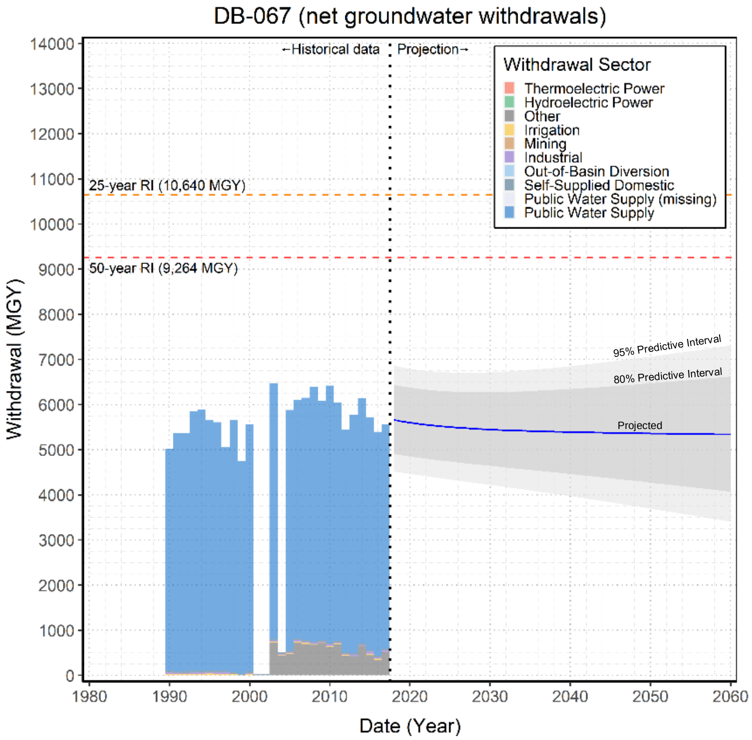


Figure 18: *Reported net groundwater withdrawals from subbasin DB-067, categorized by withdrawal sector. The projection shown is from Thompson & Pindar, 2021.*

5.1.3. Screening tool assessment

Between 2020 and 2060, net groundwater withdrawals in most subbasins are projected to stay stable relative to available groundwater. Therefore, screening-tool results for 2020 and 2060 are very similar. Percent groundwater use is often higher with the 95%PI than with the projected net withdrawal, which emphasizes the importance of accounting for uncertainty in these projections. While most subbasins do not have a significant increase in projected net groundwater withdrawals relative to available baseflow from 2020 to 2060, those that do (notably DB-145, DB-054, DB-147, DB-133, and DB-067) may be more vulnerable to a severe drought in the 2050s than they would be to a severe drought in the 2020s (Table 3).

Considering projected net withdrawals, DB-067 (Little Lehigh Creek, PA) is projected to use the highest percent of available groundwater among any subbasin: approximately 60% for RI-50 baseflow and approximately 50% for RI-25 baseflow (Figure 18, Table 3). Considering 95%PI net withdrawals, subbasin DB-067 is again projected to use the highest percent of available groundwater: approximately 80% for RI-50 baseflow and approximately 70% for RI-25 baseflow; DB-067 was the only subbasin to extend beyond 75% in any scenario calculation. Groundwater use with the 95%PI increases while there is a slight decrease in the projected value because the predictive interval's growth rate exceeds the rate of decrease of the projected net withdrawal. Of note, the Little Lehigh Creek watershed has previously been identified as an area of interest in numerous water resource studies:

- **1991**: The 80.8 mi^2 area of the Little Lehigh Creek above USGS gage 01451500 was the focus of previous modelling efforts (Sloto et al., 1991), where it was reported that average pumping from the study area was about 1,850 MGY during 1975–1983, and increased groundwater development was modeled with simulated well-fields. A general finding specific to this portion of the subbasin was that "*Model simulations show that ground-water withdrawals do not cause a proportional reduction in base flow… The effect of pumping largely depends on well location.*"
- **2006**: The groundwater availability study (Sloto & Buxton, 2006) also assessed DB-067 and concluded that water use as a percentage of available ground water was 25–50% for the RI-5, RI-10 and RI-25 baseflow scenarios, and 50–75% the RI-50 baseflow scenario.

- **2009:** During the development of the Pennsylvania State Water Plan in 2009, the Water-Analysis Screening Tool (WAST) was applied to watersheds statewide. As discussed in Section 2.4, there were thirty-two watersheds identified for review as possible critical water planning areas (CWPAs). The Technical Subcommittees of the Regional Water Resources Committees ultimately recommended twenty-three watersheds, of which the Little Lehigh Creek was one; a detailed report of supplemental documentation accompanied the recommendation (PADEP, 2009c).

Overall, the results of the screening tool assessment at the Basin-wide scale did not warrant further investigation into any of the 121 subbasins where the methodology is applicable.

An example groundwater production well
for a public water supply system in
New Castle County, Delaware.
Credit: Michael Thompson, DRBC

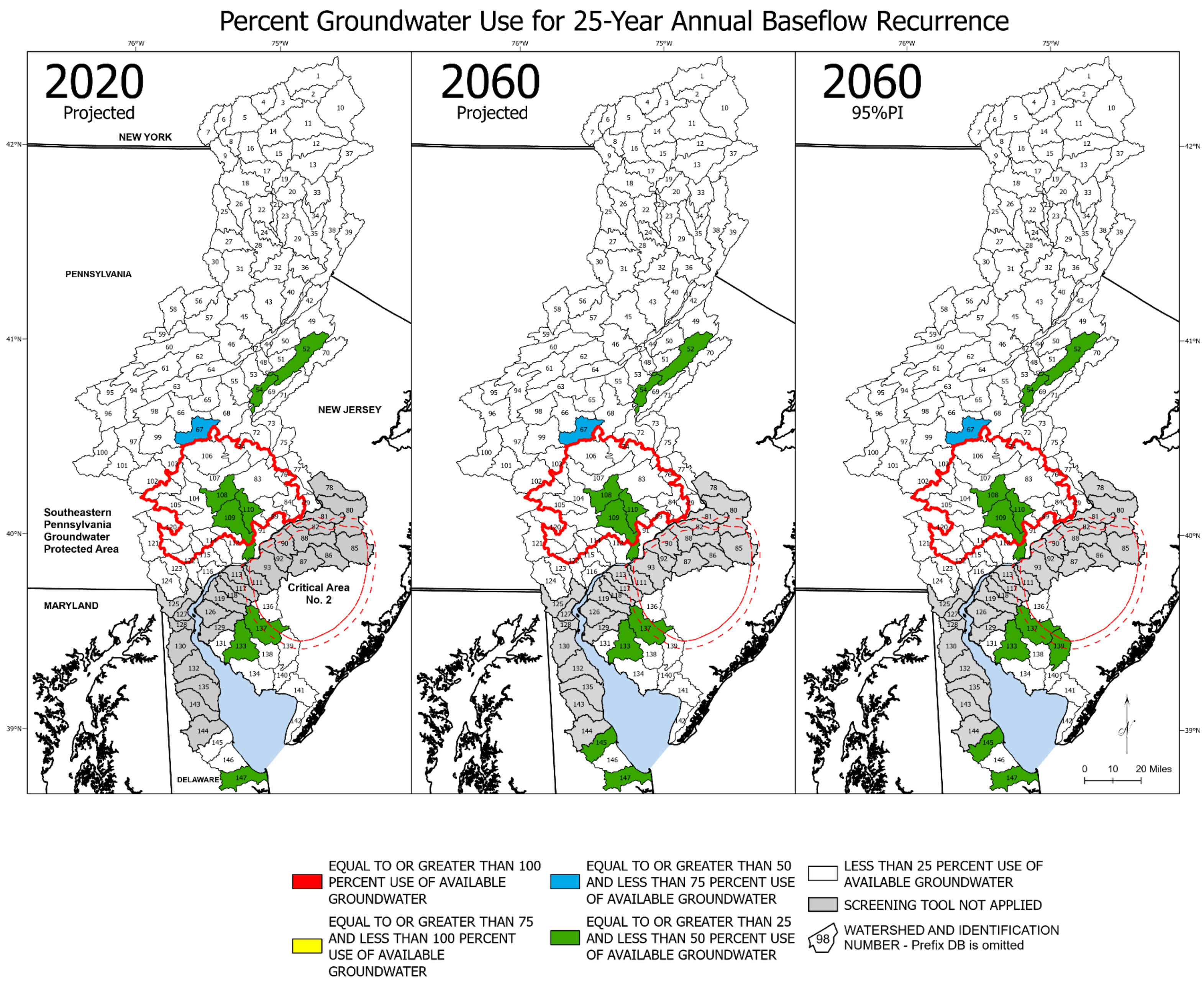


Figure 19: *Groundwater availability in each subbasin in 2020 and 2060, considering the 1-in-25-year baseflow and using projected (left and center panels) and 95%PI (right panel) net withdrawal values. The Southeastern Pennsylvania Groundwater Protected Area is shown with solid red line and Critical Area 2 with the dashed red line The screening tool was not applied to the subbasins colored gray.*

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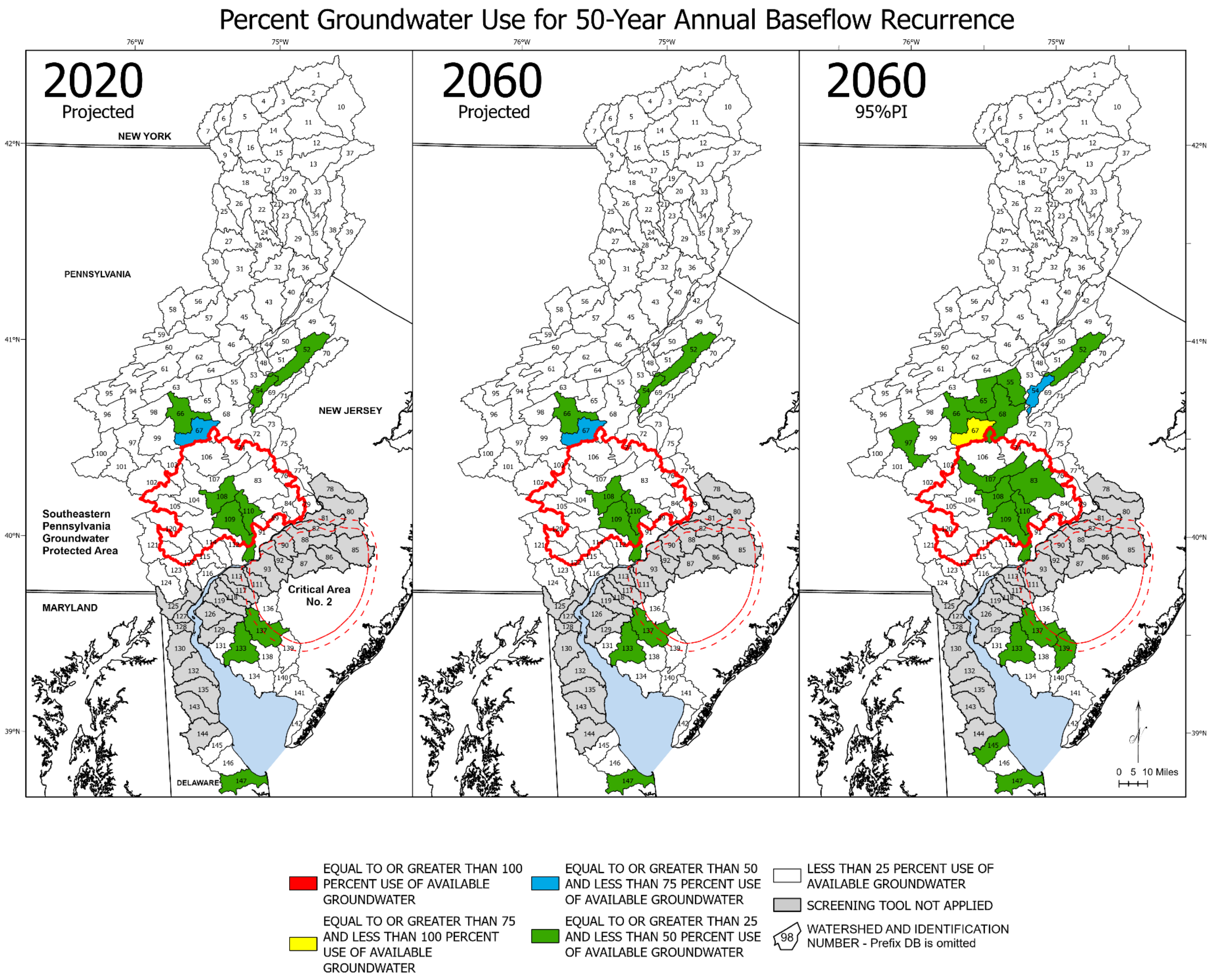

Figure 20: *Groundwater availability in each subbasin in 2020 and 2060, considering the 1-in-50-year baseflow and using projected (left and center panels) and 95%PI (right panel) net withdrawal values. The Southeastern Pennsylvania Groundwater Protected Area is shown with solid red line and Critical Area 2 with the dashed red line The screening tool was not applied to the subbasins colored gray.*

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Table 3: *Projected net and 95%PI net groundwater withdrawals presented as a percentage of 25-year and 50-year recurrence interval baseflows. The data in this table correspond with Figure 19 & Figure 20. The screening tool was not applied to the subbasins colored gray.*

Subbasin ID	Subbasin name (abbreviated)	RI-25 baseflow (MGY)	RI-50 baseflow (MGY)	Net projected values						Upper 95% predictive interval					
				Net GW (MGY)		Percent RI25		Percent RI50		Net GW (MGY)		Percent RI25		Percent RI50	
				2020	2060	2020	2060	2020	2060	2020	2060	2020	2060	2020	2060
DB-001	Upper West Branch Delaware River	21,161	19,576	236	221	1%	1%	1%	1%	296	286	1%	1%	2%	1%
DB-002	Little Delaware River	7,691	7,115	2	1	0%	0%	0%	0%	2	1	0%	0%	0%	0%
DB-003	Middle part of West Branch Delaware River	12,193	11,280	391	389	3%	3%	3%	3%	543	640	4%	6%	5%	6%
DB-004	Upr W Branch Del Riv and E Branch Del Riv	7,812	7,227	348	304	4%	4%	5%	4%	493	544	6%	7%	7%	8%
DB-005	Lower part West Branch Delaware River	18,455	17,188	5	3	0%	0%	0%	0%	5	3	0%	0%	0%	0%
DB-006	Cold Spring Creek, Butler Brook, Bone Creek	5,809	5,385	3	2	0%	0%	0%	0%	3	2	0%	0%	0%	0%
DB-007	Oquaga Creek	10,260	9,574	2	2	0%	0%	0%	0%	2	2	0%	0%	0%	0%
DB-008	Tribs to Delaware River	7,058	6,724	3	1	0%	0%	0%	0%	3	2	0%	0%	0%	0%
DB-009	Faulkner Bk, Balls Ck, Shehawken Ck, Sherman Ck	12,160	10,605	3	2	0%	0%	0%	0%	3	2	0%	0%	0%	0%
DB-010	Upr part of E Branch Delaware River above Platte Kill	31,291	29,144	139	135	0%	0%	0%	0%	183	226	1%	1%	1%	1%
DB-011	Upr part E Branch Del Riv & tribs to Pepacton Res	24,130	22,487	12	11	0%	0%	0%	0%	16	20	0%	0%	0%	0%
DB-012	Upper part of Beaver Kill	15,820	15,203	1	1	0%	0%	0%	0%	1	1	0%	0%	0%	0%
DB-013	Willowemoc Creek	21,350	20,644	174	154	1%	1%	1%	1%	214	198	1%	1%	1%	1%
DB-014	Mid E Branch Delaware Riv below Pepacton Reservoir	14,233	13,390	3	2	0%	0%	0%	0%	3	2	0%	0%	0%	0%
DB-015	Lower part of Beaver Kill	10,566	10,214	2	1	0%	0%	0%	0%	2	1	0%	0%	0%	0%
DB-016	Lower part East Branch Delaware River	12,565	12,086	118	82	1%	1%	1%	1%	167	142	1%	1%	1%	1%
DB-017	Hankins Ck and tribs to Delaware River	10,710	10,508	49	47	0%	0%	0%	0%	62	63	1%	1%	1%	1%
DB-018	Equinunk Creek	25,138	21,524	6	4	0%	0%	0%	0%	6	4	0%	0%	0%	0%
DB-019	East Branch Callicoon Creek	4,136	4,048	3	2	0%	0%	0%	0%	3	2	0%	0%	0%	0%
DB-020	North Branch Callicoon Creek	11,026	10,846	32	25	0%	0%	0%	0%	42	36	0%	0%	0%	0%
DB-021	Unnamed tributaries to Delaware River	2,910	2,847	27	22	1%	1%	1%	1%	32	28	1%	1%	1%	1%
DB-022	Caulkins Creek and tribs to Delaware River	16,180	13,828	18	16	0%	0%	0%	0%	22	22	0%	0%	0%	0%
DB-023	Ten Mile River	6,754	6,614	3	2	0%	0%	0%	0%	3	2	0%	0%	0%	0%
DB-024	Masthope Ck, Westcolang Ck	7,972	6,808	117	132	2%	2%	2%	2%	147	160	2%	2%	2%	2%
DB-025	West Branch Lackawaxen River	18,648	15,957	306	513	2%	3%	2%	3%	382	591	2%	4%	2%	4%
DB-026	Dyberry Creek	14,156	12,088	10	9	0%	0%	0%	0%	11	11	0%	0%	0%	0%
DB-027	Middle Creek	16,656	14,499	34	25	0%	0%	0%	0%	48	40	0%	0%	0%	0%
DB-028	Lackawaxen River	25,486	21,809	229	148	1%	1%	1%	1%	310	229	1%	1%	1%	1%
DB-029	Fish Cabin Creek and tribs to Delaware River	13,710	12,969	11	7	0%	0%	0%	0%	11	8	0%	0%	0%	0%
DB-030	West Branch Wallenpaupack Creek	13,689	12,028	74	71	1%	1%	1%	1%	97	106	1%	1%	1%	1%
DB-031	Wallenpaupack Creek	32,371	28,178	405	409	1%	1%	1%	1%	548	561	2%	2%	2%	2%
DB-032	Shohola Creek, Panther Creek	18,721	16,020	207	202	1%	1%	1%	1%	362	468	2%	3%	2%	3%
DB-033	Mongaup River above Swinging Bridge Reservoir	11,809	11,036	231	207	2%	2%	2%	2%	314	315	3%	3%	3%	3%
DB-034	Mongaup River tributaries to Swinging Bridge Reservoir	6,014	5,595	23	20	0%	0%	0%	0%	49	78	1%	2%	1%	2%
DB-035	Mongaup Riv below Swinging Bridge Res, Shingle Kill	16,957	15,908	17	14	0%	0%	0%	0%	18	18	0%	0%	0%	0%
DB-036	Walker Lake Creek and tribs to Delaware River	15,729	13,968	220	218	1%	1%	2%	2%	291	299	2%	2%	2%	2%
DB-037	Neversink River above Neversink Reservoir	14,547	13,766	2	1	0%	0%	0%	0%	2	2	0%	0%	0%	0%
DB-038	Neversink River below Neversink Reservoir	30,773	28,310	1060	878	3%	3%	4%	3%	1786	1897	6%	6%	6%	6%
DB-039	Basher Kill	11,784	10,794	139	151	1%	1%	1%	1%	196	206	2%	2%	2%	2%
DB-040	Raymondskill Creek and tribs to Delaware River	17,134	15,488	182	176	1%	1%	1%	1%	229	236	1%	1%	1%	2%
DB-041	Unnamed tributary to Delaware River	3,426	3,149	1	1	0%	0%	0%	0%	1	1	0%	0%	0%	0%
DB-042	Flat Brook	11,106	9,864	6	4	0%	0%	0%	0%	6	4	0%	0%	0%	0%

Table 3 (continued): *Projected net and 95%PI net groundwater withdrawals presented as a percentage of 25-year and 50-year recurrence interval baseflows. The data in this table correspond with Figure 19 & Figure 20. The screening tool was not applied to the subbasins colored gray.*

Subbasin ID	Subbasin name (abbreviated)	RI-25 baseflow (MGY)	RI-50 baseflow (MGY)	Net projected values						Upper 95% predictive interval					
				Net GW (MGY)		Percent RI25		Percent RI50		Net GW (MGY)		Percent RI25		Percent RI50	
				2020	2060	2020	2060	2020	2060	2020	2060	2020	2060	2020	2060
DB-043	Bush Kill	31,548	27,313	551	723	2%	2%	2%	3%	732	884	2%	3%	3%	3%
DB-044	Vancampens Brook, Dunnfiled Creek	4,824	4,190	2	2	0%	0%	0%	0%	2	2	0%	0%	0%	0%
DB-045	Brodhead Creek	34,682	30,286	1325	1907	4%	5%	4%	6%	2023	2523	6%	8%	7%	9%
DB-046	Pocono Creek	22,379	19,862	332	348	2%	2%	2%	2%	427	488	2%	2%	2%	3%
DB-047	Cherry Creek, Caledonia Creek	5,999	5,373	253	241	4%	4%	5%	4%	456	446	8%	8%	8%	8%
DB-048	Slateford Creek, Jacoby Creek, Allegheny Creek	3,948	3,065	57	44	1%	1%	2%	1%	81	74	2%	2%	3%	2%
DB-049	Paulins Kill above Stillwater Village, Trout Brook	13,836	11,186	481	561	4%	4%	4%	5%	623	701	5%	5%	6%	6%
DB-050	Paulins Kill (below Stillwater Village)	8,944	7,239	27	23	0%	0%	0%	0%	27	24	0%	0%	0%	0%
DB-051	Stony Brook, Delawanna Creek, Beaver Brook	6,290	5,077	117	146	2%	2%	2%	3%	148	175	2%	3%	3%	4%
DB-052	Pequest River	15,888	13,539	4013	4289	26%	27%	30%	32%	4516	4763	28%	30%	33%	36%
DB-053	Martins Creek, Mud Run	9,735	7,746	578	663	6%	7%	7%	9%	874	1047	9%	11%	11%	14%
DB-054	Pophandusing Bk, Buckhorn Ck, Lopatcong Ck	6,123	5,327	1869	1859	30%	30%	35%	35%	2459	2860	40%	50%	46%	57%
DB-055	Bush Kill	10,093	8,224	232	228	2%	2%	3%	3%	338	322	3%	3%	4%	4%
DB-056	Upper part of Lehigh River	18,952	16,630	71	69	0%	0%	0%	0%	104	128	1%	1%	1%	1%
DB-057	Tobyhanna Creek	26,135	22,938	783	1070	3%	4%	3%	5%	1016	1242	4%	5%	4%	6%
DB-058	Bear Creek	19,076	16,595	43	48	0%	0%	0%	0%	52	56	0%	0%	0%	0%
DB-059	Middle part of Lehigh River above Sandy Run	10,506	9,104	115	96	1%	1%	1%	1%	177	192	2%	2%	2%	2%
DB-060	Middle part of Lehigh River above Black Creek	31,314	27,228	178	167	1%	1%	1%	1%	278	284	1%	1%	1%	1%
DB-061	Middle part of Lehigh River above Pohopoco Creek	23,777	21,064	502	381	2%	2%	2%	2%	767	566	3%	2%	4%	3%
DB-062	Pohopoco Creek	21,905	19,396	302	286	1%	1%	2%	1%	645	800	3%	4%	3%	5%
DB-063	Lower part of Lehigh River	18,423	15,707	436	422	2%	2%	3%	3%	523	600	3%	3%	3%	4%
DB-064	Aquashicola Creek	14,527	12,946	349	469	3%	3%	3%	4%	452	559	3%	4%	3%	5%
DB-065	Lower part of Lehigh River above Little Lehigh Creek	11,611	9,381	915	926	8%	8%	10%	10%	1354	1423	12%	13%	14%	16%
DB-066	Jordan Creek	13,451	10,721	2689	2126	18%	16%	25%	20%	3478	3090	26%	23%	32%	28%
DB-067	Little Lehigh Creek	10,640	9,264	5601	5338	51%	50%	60%	58%	6794	7065	64%	69%	73%	79%
DB-068	Lower part of Lehigh River below Little Lehigh Creek	18,419	15,849	1128	1425	6%	8%	7%	9%	1467	1695	8%	10%	9%	11%
DB-069	Pohatcong Creek	7,901	6,754	396	444	5%	6%	6%	7%	674	774	9%	10%	10%	12%
DB-070	Musconetcong River above Trout Brook	12,303	10,282	1296	1404	11%	11%	13%	14%	1654	1748	13%	15%	16%	17%
DB-071	Musconetcong River below and including Trout Brook	10,064	8,500	764	781	8%	8%	9%	9%	1142	1190	11%	12%	13%	14%
DB-072	Frya Run, Cooks Creek, Tinicum Creek	8,874	7,615	102	103	1%	1%	1%	1%	121	124	1%	1%	2%	2%
DB-073	Harihokake Creek, Nishisakawick Creek	4,872	4,138	144	109	3%	2%	3%	3%	194	166	4%	3%	5%	4%
DB-074	Tohichon Creek	7,172	6,140	1103	1197	16%	17%	18%	19%	1320	1407	18%	20%	21%	23%
DB-075	Lockatong Creek, Wickecheoke Creek	4,121	3,498	111	115	3%	3%	3%	3%	150	167	4%	4%	4%	5%
DB-076	Geddes Run and tribs to Delaware River	7,150	6,133	454	470	6%	7%	7%	8%	584	654	8%	10%	10%	11%
DB-077	Alexauken Creek, Moores Creek, Jacobs Creek	4,618	3,930	142	122	3%	3%	4%	3%	210	178	5%	4%	5%	4%
DB-078	Assunpink Creek	23,430	22,347	1755	1891					1985	2118				
DB-079	Martins Creek, and tributaries to Delaware River	5,715	5,401	413	529	8%	9%	8%	10%	716	682	13%	12%	13%	13%
DB-080	Crosswicks Creek	17,221	16,115	1692	1298					2391	2173				
DB-081	Crafts Creek, Blacks Creek	6,246	5,845	1912	2269					2402	2714				
DB-082	Assiscunk Creek and tributaries to Delaware River	9,769	9,052	1003	686					1459	1337				
DB-083	Neshaminy Creek above Little Neshaminy Creek	15,511	13,024	1946	2034	13%	13%	15%	16%	2699	2737	17%	18%	21%	21%
DB-084	Neshaminy Creek below Little Neshaminy Creek	7,409	6,483	396	214	4%	3%	6%	3%	445	325	6%	4%	7%	5%

Table 3 (continued): *Projected net and 95%PI net groundwater withdrawals presented as a percentage of 25-year and 50-year recurrence interval baseflows. The data in this table correspond with Figure 19 & Figure 20. The screening tool was not applied to the subbasins colored gray.*

Subbasin ID	Subbasin name (abbreviated)	RI-25 baseflow (MGY)	RI-50 baseflow (MGY)	Net projected values						Upper 95% predictive interval					
				Net GW (MGY)		Percent RI25		Percent RI50		Net GW (MGY)		Percent RI25		Percent RI50	
				2020	2060	2020	2060	2020	2060	2020	2060	2020	2060	2020	2060
DB-085	N Branch Rancocas Ck, Greenwood Bk	20,297	18,807	412	275					629	551				
DB-086	S Branch Rancocas Creek above Bobbys Run	12,625	11,698	335	254					544	505				
DB-087	South Branch Rancocas Creek above SW Branch	13,990	12,963	1450	1384					1894	1908				
DB-088	N & S Branch Rancocas Creek	17,629	16,335	2046	1926					2700	2714				
DB-089	Poquessing Creek, Pennypack Creek	8,885	8,113	561	450	6%	5%	7%	6%	841	753	9%	8%	10%	9%
DB-090	Pennsauken Creek, Pompeston Creek	8,062	8,001	4698	4076					6499	6032				
DB-091	Frankford Ck and tribs to Delaware River	6,931	6,572	71	97	1%	1%	1%	1%	100	127	1%	2%	2%	2%
DB-092	Cooper River	7,358	7,302	6868	6453					8848	9145				
DB-093	Woodbury Ck, Big Timber Ck, Newton Ck	14,191	14,083	6172	5424					7954	7327				
DB-094	Little Schuylkill River	27,124	23,732	109	97	0%	0%	0%	0%	158	162	1%	1%	1%	1%
DB-095	Upr part of Schuylkill Riv above Pottsville	14,247	12,327	147	141	1%	1%	1%	1%	329	349	2%	3%	3%	3%
DB-096	Upper part of Schuylkill Riv below Pottsville	26,961	23,943	225	182	1%	1%	1%	1%	310	289	1%	1%	1%	1%
DB-097	Tributaries to middle part of Schuylkill River	14,111	11,211	1823	1461	12%	10%	16%	13%	3025	2839	21%	20%	27%	25%
DB-098	Maiden Creek above Saucony Creek	12,148	9,408	206	225	2%	2%	2%	2%	283	312	2%	3%	3%	3%
DB-099	Maiden Creek below Saucony Creek	15,992	13,180	1245	1571	8%	10%	9%	12%	1573	1851	10%	12%	12%	15%
DB-100	Upper Tulpehocken Creek above Blue Marsh Res	16,453	13,577	557	655	4%	4%	4%	5%	759	886	5%	6%	6%	7%
DB-101	Lower Tulpehocken Creek below Blue Marsh Res	11,439	9,287	1168	1242	10%	11%	13%	13%	1337	1387	12%	12%	14%	15%
DB-102	Tributaries to Lower Middle Schuylkill River	18,385	15,432	1211	1037	6%	6%	8%	7%	1511	1301	8%	7%	10%	8%
DB-103	Manatawny Creek	11,722	9,922	212	216	2%	2%	2%	2%	243	257	2%	2%	2%	3%
DB-104	Lwr part of Schuylkill Riv and tribs above Skippack Ck	12,726	11,318	936	868	7%	7%	8%	8%	1483	1436	12%	11%	13%	13%
DB-105	French Creek	7,697	6,813	146	160	2%	2%	2%	2%	214	244	3%	3%	3%	4%
DB-106	West Branch Perkiomen Creek	13,315	11,211	897	1211	7%	9%	8%	11%	1169	1493	9%	12%	10%	14%
DB-107	Perkiomen Creek above and including East	9,431	8,064	1431	1595	16%	17%	18%	20%	1813	1965	19%	21%	22%	25%
DB-108	Perkiomen Creek below East Branch	5,605	4,781	1416	1480	25%	26%	30%	31%	1853	1914	33%	35%	39%	40%
DB-109	Lwr part of Schuylkill Riv & tribs below Skippack Ck	14,249	12,837	3769	3612	26%	25%	29%	28%	4667	4985	33%	36%	36%	40%
DB-110	Wissahickon Creek	6,795	5,951	2398	1933	33%	28%	40%	32%	2969	2567	44%	36%	50%	42%
DB-111	Mantua Creek	7,195	7,140	2125	1650					3049	2653				
DB-112	Darby Creek	8,617	8,157	21	21	0%	0%	0%	0%	49	53	1%	1%	1%	1%
DB-113	Cedar Swamp, Repaupo Ck, Clonmell Ck	10,302	10,033	946	783					1357	1222				
DB-114	Crum Creek, Ridley Creek, Marcus Hook Creek	8,142	7,720	74	65	1%	1%	1%	1%	119	118	1%	1%	2%	1%
DB-115	Chester Creek	7,010	6,636	35	36	1%	1%	1%	1%	54	47	1%	1%	1%	1%
DB-116	Naamans Creek, Shellpot Creek	4,243	4,017	16	17	0%	0%	0%	0%	31	70	1%	2%	1%	2%
DB-117	Raccoon Creek & Birch Creek	6,243	4,810	1104	1128					1575	1618				
DB-118	Oldmans Creek	5,530	4,260	580	606					838	983				
DB-119	Salem River above dam, Salem Canal	18,070	17,598	2155	1973					3111	2964				
DB-120	East Branch Brandywine Creek	13,163	12,383	1811	1868	14%	14%	15%	15%	2196	2267	17%	18%	18%	19%
DB-121	West Branch Brandywine Creek	14,307	13,549	630	884	5%	6%	5%	7%	906	1154	6%	9%	7%	9%
DB-122	Brandywine Creek (main stem)	6,888	6,521	49	48	1%	1%	1%	1%	74	77	1%	1%	1%	1%
DB-123	Red Clay Creek	5,951	5,626	233	291	4%	5%	4%	5%	349	430	6%	7%	6%	8%
DB-124	White Clay Creek	11,042	10,439	763	780	7%	7%	7%	7%	1081	1145	10%	11%	10%	11%
DB-125	Christina River and tribs to Delaware River	8,901	8,434	1565	1529					2347	2332				
DB-126	Salem River below dam	17,284	16,831	443	381					686	560				

Table 3 (continued): *Projected net and 95%PI net groundwater withdrawals presented as a percentage of 25-year and 50-year recurrence interval baseflows. The data in this table correspond with Figure 19 & Figure 20. The screening tool was not applied to the subbasins colored gray.*

Subbasin ID	Subbasin name (abbreviated)	RI-25 baseflow (MGY)	RI-50 baseflow (MGY)	Net projected values						Upper 95% predictive interval					
				Net GW (MGY)		Percent RI25		Percent RI50		Net GW (MGY)		Percent RI25		Percent RI50	
				2020	2060	2020	2030	2020	2060	2020	2060	2020	2060	2020	2060
DB-127	Army Creek, Red Lion Creek, Dragon Creek	6,117	5,921	3735	3703					5139	5311				
DB-128	C and D Canal and tributaries to Delaware Bay	3,284	3,154	173	166					288	297				
DB-129	Alloway Creek, Hope Creek	19,518	19,007	401	416					579	802				
DB-130	Augustine Creek, Appoquinimik River, Blackbird Creek	7,781	5,919	763	1528					1031	1658				
DB-131	Stow Creek and tributaries to Delaware Bay	9,718	8,932	127	124	1%	1%	1%	1%	239	268	2%	3%	3%	3%
DB-132	Smyrna River, Duck Creek, Mill Creek	10,118	9,717	625	618					816	856				
DB-133	Cohansey River	19,907	18,382	5452	6409	30%	32%	30%	35%	7040	8456	35%	42%	38%	45%
DB-134	Back Ck, Cedar Ck, Nantuxent Ck, Dividing Ck	19,538	17,958	653	721	4%	4%	4%	4%	875	1015	4%	5%	5%	5%
DB-135	Leipsic River, Simons River, Little River	8,580	6,527	945	1091					1245	1399				
DB-136	Scotland Run, Still Run, & Little Ease Run	12,696	11,947	1945	1956	15%	15%	16%	16%	2690	2876	21%	23%	23%	24%
DB-137	Maurice Riv above Sherman Ave Bridge & Muddy Run	19,175	18,044	5550	5433	29%	28%	31%	30%	7534	7956	39%	40%	42%	43%
DB-138	Maurice River above Menantico Creek	11,646	10,959	1886	1875	16%	16%	17%	17%	2271	2367	19%	20%	21%	21%
DB-139	Menantico Creek, Manamuskin River	12,608	11,865	2411	2612	20%	21%	20%	22%	3228	3735	26%	30%	27%	32%
DB-140	Maurice River below Menantico Creek	12,291	11,969	122	176	1%	1%	1%	1%	140	188	1%	2%	1%	2%
DB-141	West Creek, East Creeks, Dennis Creek	21,726	21,158	467	556	2%	3%	2%	3%	590	673	3%	3%	3%	3%
DB-142	Tributaries to Delaware Bay	11,355	11,058	1750	2021	16%	18%	16%	18%	2047	2271	18%	21%	19%	21%
DB-143	Saint Jones River	7,543	5,738	2154	1974					2907	2751				
DB-144	Murderkill River	8,896	6,767	1059	1248					1423	1746				
DB-145	Mispillion River and tributaries to Delaware Bay	6,387	4,859	1188	1812	21%	28%	24%	37%	1470	1980	23%	33%	30%	44%
DB-146	Cedar Creek, Slaughter Creek, Primehook Creek	7,113	5,410	919	977	13%	14%	17%	18%	1134	1250	16%	17%	21%	23%
DB-147	Round Pole Branch and tributaries to Delaware Bay	8,473	8,138	2411	2849	30%	34%	30%	35%	3093	3655	36%	44%	38%	46%

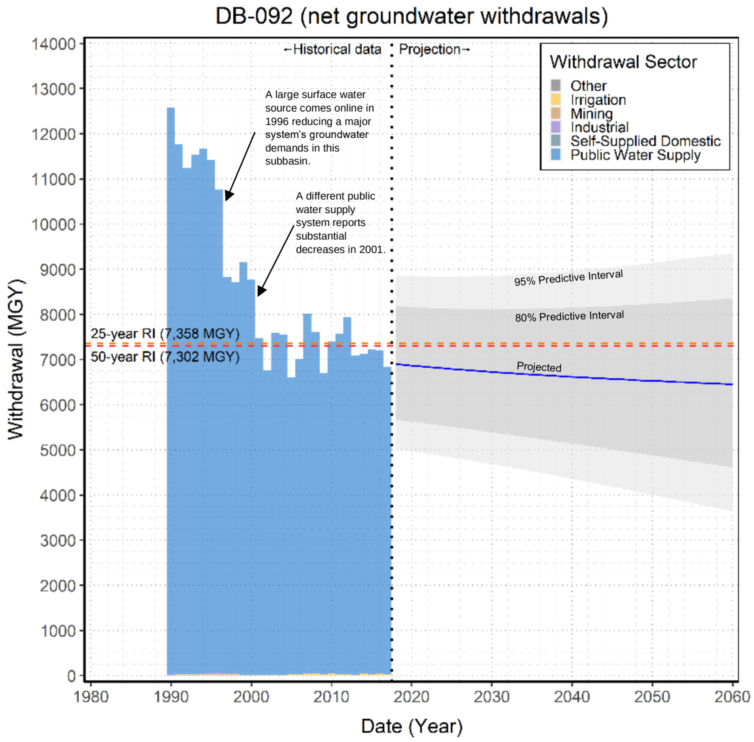


Figure 21: *Reported net groundwater withdrawals from subbasin DB-092, categorized by withdrawal sector. Additional data for one public water utility has been added to the historical data set since the publication of Thompson & Pindar, 2021. The projection shown is directly from Thompson & Pindar, 2021.*

5.1.4. Atlantic coastal plain

5.1.4.1. Case study (DB-092)

The Sloto & Buxton, 2006 screening tool was initially used to assess groundwater availability in all 147 subbasins within the Delaware River Basin. The projected net groundwater withdrawal in one subbasin, DB-092 ("Cooper River" in the New Jersey Coastal Plain), exceeded 100% of estimated baseflow. A detailed assessment of this subbasin led to the conclusion that the Sloto & Buxton, 2006 screening tool is not applicable based on the assumptions and limitations of the methodology. Two primary findings from this DB-092 case study are discussed below.

1. The 95%PI net groundwater withdrawals exceed estimated RI-25 and RI-50 baseflows in DB-092. There are data for 131 groundwater sources in DB-092 (historical and present), of which 54 sources reported non-zero withdrawals in 2017, ranging from 0.02 to 530 MGY. As reported in Table 3, the projected net annual groundwater withdrawal from DB-092 in 2020 was 6,868 million gallons, expected to decrease to 6,453 million gallons in 2060 (Thompson & Pindar, 2021). Quantifying uncertainty in this projection results in a 95%PI in 2060 of 9,363 million gallons (as shown in Figure 21). If net groundwater withdrawals were to increase toward the upper predictive limit in 2060 (rather than decreasing to the projected value), net withdrawals would be above 100% of the estimated available baseflow at both 25- and 50-year recurrence intervals.

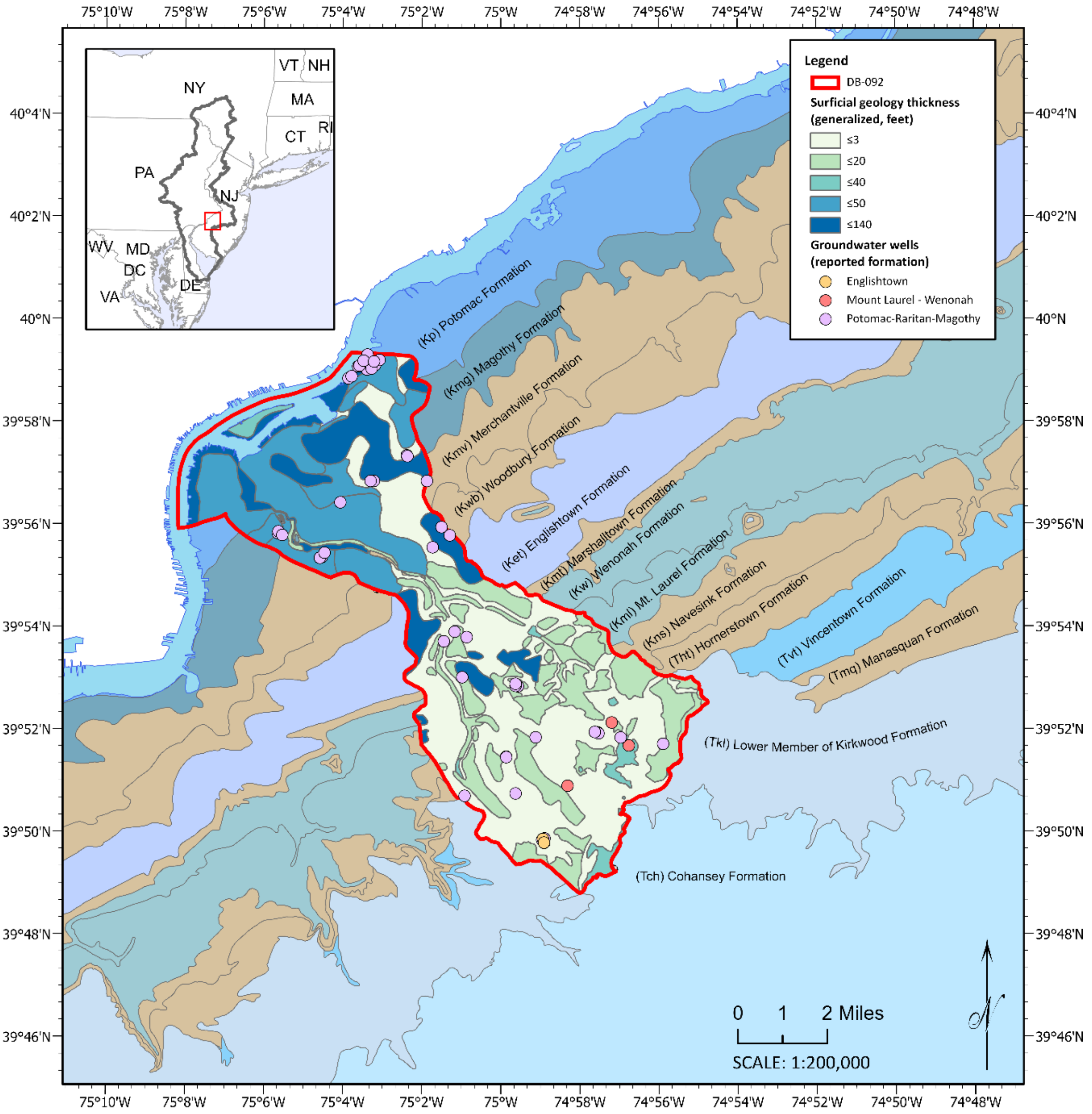


Figure 22: The 54 groundwater wells which reported non-zero withdrawals in 2017 from subbasin DB-092, color coded by the formation in which the well is finished (per reported data). These points are plotted in conjunction with the surficial lithology layer initially shown in Figure 9, with the data re-color-coded by the thickness of the surficial layer based on the geologic description. The Coastal Plain formations as portrayed by NJDEP, 2019 are shown as underlying the surficial geology, corresponding to the geologic cross-section adopted from dePaul et al., 2009 in Figure 10.

2. Based on 2017 withdrawal volumes, it is estimated that over 97% of the withdrawals in subbasin DB-092 were from the Potomac–Raritan–Magothy (PRM) formations, about 2.5% from the Englishtown formation, and the remainder from the Wenonah–Mt. Laurel formations, with very little (if any) from the surficial geology or unconfined aquifers. All 54 sources reporting withdrawals in 2017 have well construction details available which include either total depth or depth to the top of the screened interval, and information on the formation in which they were completed. The minimum finished depth of these wells is 124 feet below ground surface (ft-bgs) and ranges up to 1,099 ft-bgs. A comparison of the individual well construction information against the available data for

surficial geology is presented in Figure 22. This analysis shows that wells are predominantly installed below the surficial geology and withdraw water from the underlying network of confined aquifers. Many wells are even installed through the higher confined aquifers (e.g., the Englishtown formation) and extend into lower confined aquifers (such as the PRM formation).

Considering these findings, it is important to re-iterate a primary assumption made in Sloto & Buxton, 2006 regarding the Coastal Plain: "*The watershed approach and equating availability to stream base flow is not suited for estimating confined aquifer groundwater availability. Determining the source of groundwater withdrawals in a confined system is a complex regional issue. The effects of pumping can extend well beyond watershed boundaries and even beyond the Delaware River Basin.*" Based on the analysis presented in this section and the assumptions/limitations of the methodology proposed in Sloto & Buxton, 2006, it is apparent that this methodology is not well suited for DB-092 as nearly all of the groundwater withdrawals are from the underlying confined aquifer network. Consequently, these findings highlight a necessity for broader investigation into the Sloto & Buxton, 2006 screening tool's applicability to the Coastal Plain portion of the Delaware River Basin, which is presented in the following section.

5.1.4.2. Screening tool applicability to Coastal Plain subbasins

Findings from the assessment of DB-092 in Section 5.1.4 necessitate investigation into whether the Sloto & Buxton, 2006 screening methodology is appropriate for the Coastal Plain. For the methodology to be applicable in a subbasin, wells in that subbasin must primarily withdraw groundwater from surficial, unconfined aquifers (not from underlying confined aquifers).

Construction details are available for most groundwater wells in the states of Delaware and New Jersey. Two useful parameters are "*final installed depth*" and "*depth to the top of screened interval*" (an interval where groundwater can enter the well casing), both measured in feet below ground surface (ft-bgs). The average total withdrawal (in MGY) was calculated for all Delaware River Basin wells in the Coastal Plain portions of Delaware and New Jersey from 2013 to 2017. These withdrawals are plotted according to the well depth (or screened interval if depth was unavailable) as colored horizontal bars in Figure 23, corresponding with the lower x-axis. Where construction details were not available, the average total withdrawal was plotted at 0 ft-bgs. A cumulative percent of average total withdrawal at or above each depth is plotted as the red line, corresponding with the upper x-axis. This assessment demonstrates that most water (>90%) is likely withdrawn from the underlying confined aquifer network (>50 ft-bgs). However, spatial variation needs to be considered, as the confined aquifer network is complex and dips at an angle.

New Jersey groundwater well documentation specifies in which geologic formation each source is finished (for example, one well plotting over the Englishtown formation might actually be installed in the underlying PRM aquifer system). Figure 24 shows groundwater sources in New Jersey plotted over the underlying geology, color coded by formation in which the well is reported to be finished. For consistency across regional boundaries, the aquifer extents presented are based on Pope et al., 2016, although it is understood that these boundaries vary slightly from and have lower spatial resolution than data available through NJDEP (NJDEP, 2019). From this analysis and a conceptual understanding of the aquifer network structure (Figure 10), groundwater withdrawals from a predominantly unconfined aquifer (the Kirkwood-Cohansey formation) only occur in a portion of the New Jersey Coastal Plain within the Basin. Therefore, it is assumed that the Sloto & Buxton, 2006 screening methodology can sufficiently be applied to the ten subbasins at the southernmost part of New Jersey (DB-131 -133, -134, -136, -137, -138, -139, -140, -141 and -142). The remaining eighteen subbasins in the New Jersey Coastal Plain are assumed to be characterized by groundwater withdrawals from confined aquifers; therefore, the Sloto & Buxton, 2006 screening methodology is not applied to these areas. These eighteen subbasins are highlighted in Figure 26, correspondingly grayed out in Figure 19 and Figure 20**:**, and results are not populated in Table 3.

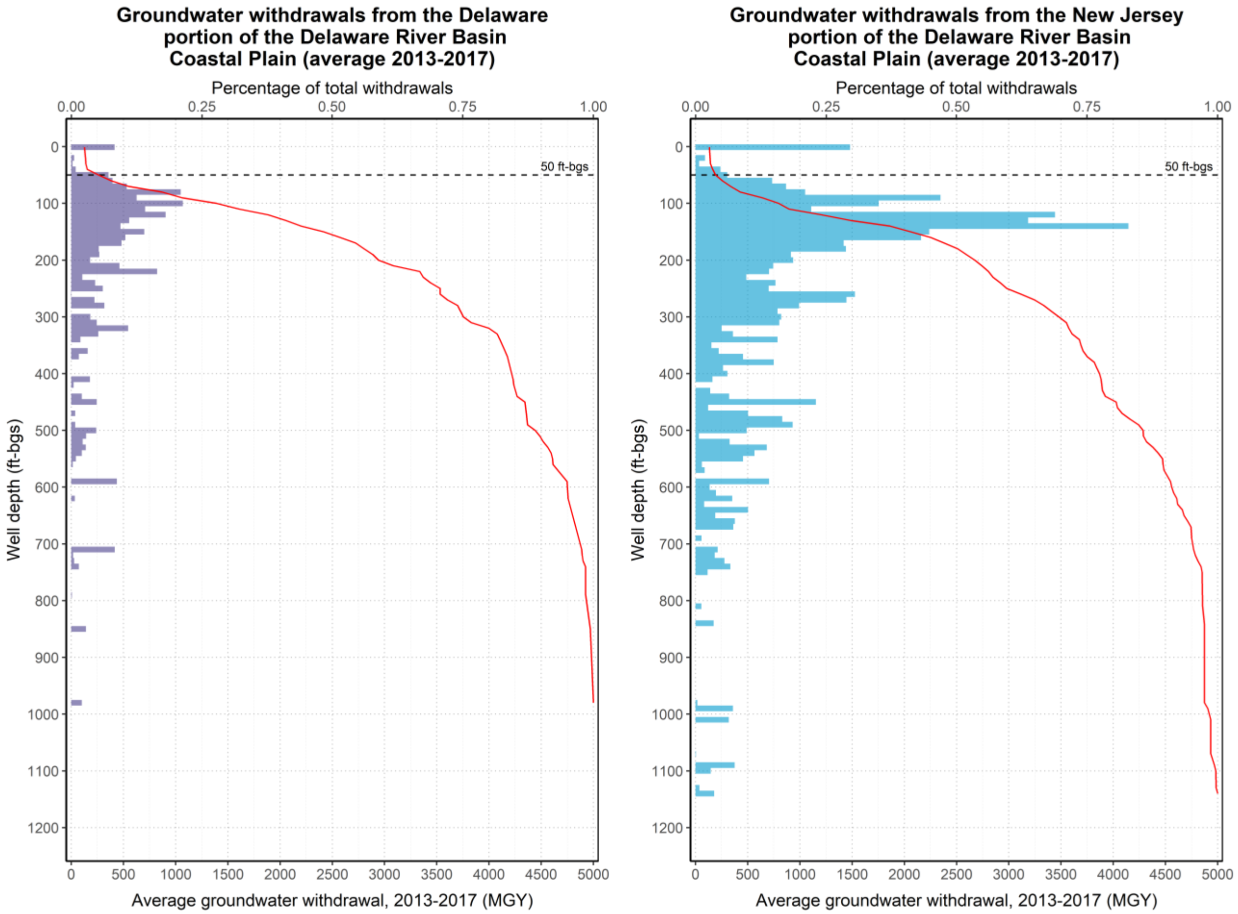


Figure 23: *Groundwater withdrawals (total) from the Delaware River Basin portions of the Coastal Plain in Delaware and New Jersey. Groundwater withdrawals (average 2013–2017, in MGY) are shown on the vertical axis as horizontal bars, read against the bottom horizontal axis. Well depths were taken as the completed well depth, or top of screened interval (whatever data were available). Data shown at a depth of zero ft-bgs are data from wells without representative metadata (e.g., well clusters reported as one source). The cumulative percentage of total withdrawals is shown by the red line, corresponding with the top axis.*

Determining areas within the Delaware Coastal Plain where the Sloto & Buxton, 2006 screening methodology may be applicable is less straightforward, as groundwater source information on geologic formation is not readily available. However, USGS has a spatial dataset for the thickness of surficial unconfined aquifers over most of the Maryland and Delaware portions of the Delmarva Peninsula (Denver & Nardi, 2016). This information can be used in conjunction with well depth information as shown in to assess whether or not wells are completed within the surficial unconfined aquifer, as shown in Figure 25. This information is then also plotted in Figure 24 over the underlying aquifer network, color coded by whether the well is deeper than the unconfined aquifer. Based on these findings, it is assumed that the Sloto & Buxton, 2006 screening methodology can sufficiently be applied to the three southernmost subbasins within Delaware (DB-145, -146, -147). The remaining eight subbasins in the Delaware Coastal Plain are assumed to be characterized by groundwater withdrawals from confined aquifers; therefore, the Sloto & Buxton, 2006 screening methodology is not applied to these areas. These eight subbasins are highlighted in Figure 26, correspondingly grayed out Figure 19 and Figure 20**:**, and results are not populated in Table 3.

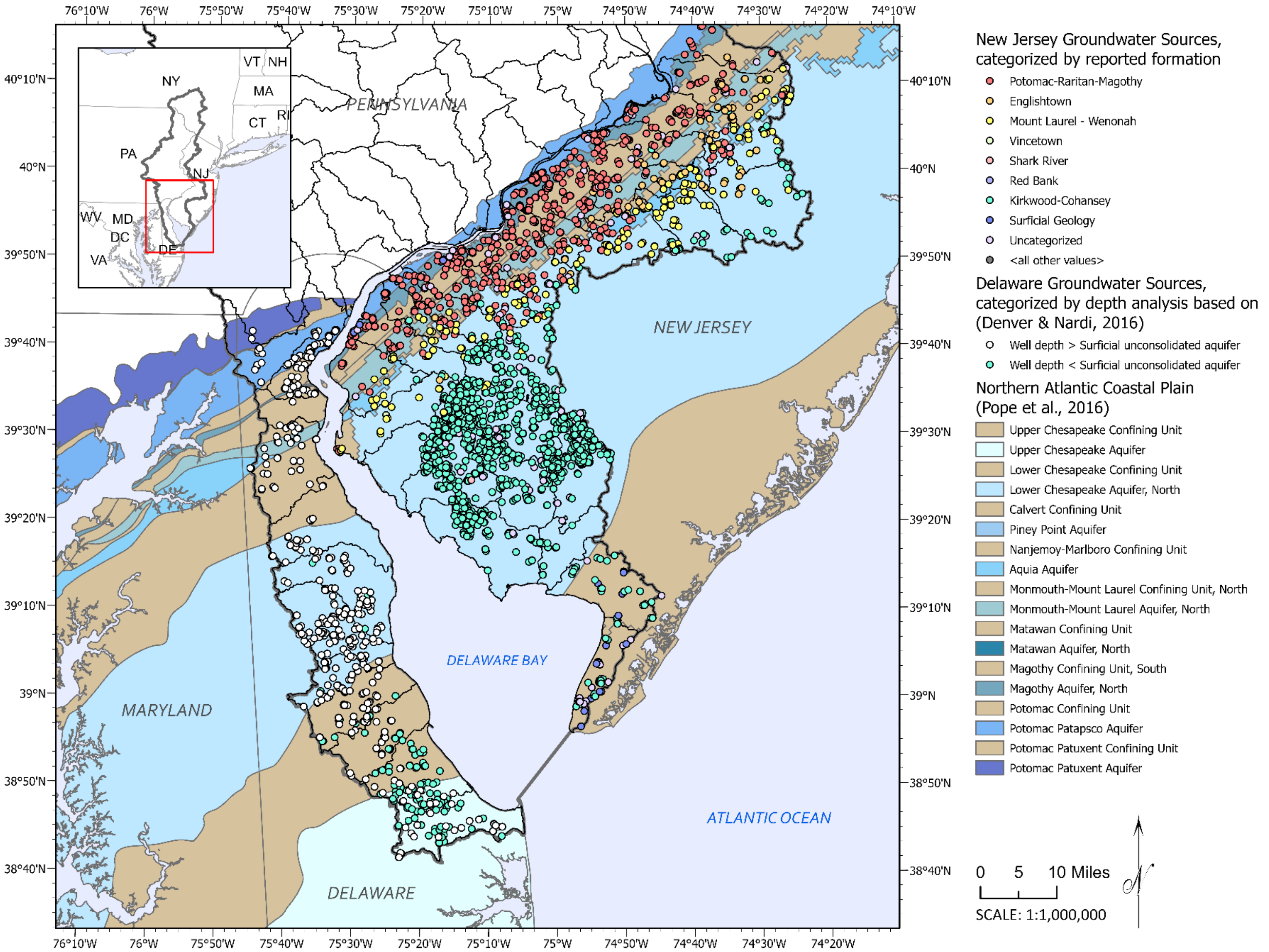


Figure 24: *Regional hydrogeologic units in the North Atlantic Coastal Plain Aquifer as presented in Pope et al., 2016, which have been normalized across regional boundaries using consistent nomenclature. Groundwater sources in New Jersey are plotted according to the reported formation each well is finished in. Groundwater sources in Delaware are color coded based on whether or not the well depth extends below the surficial unconfined aquifer thickness reported in Denver & Nardi, 2016.*

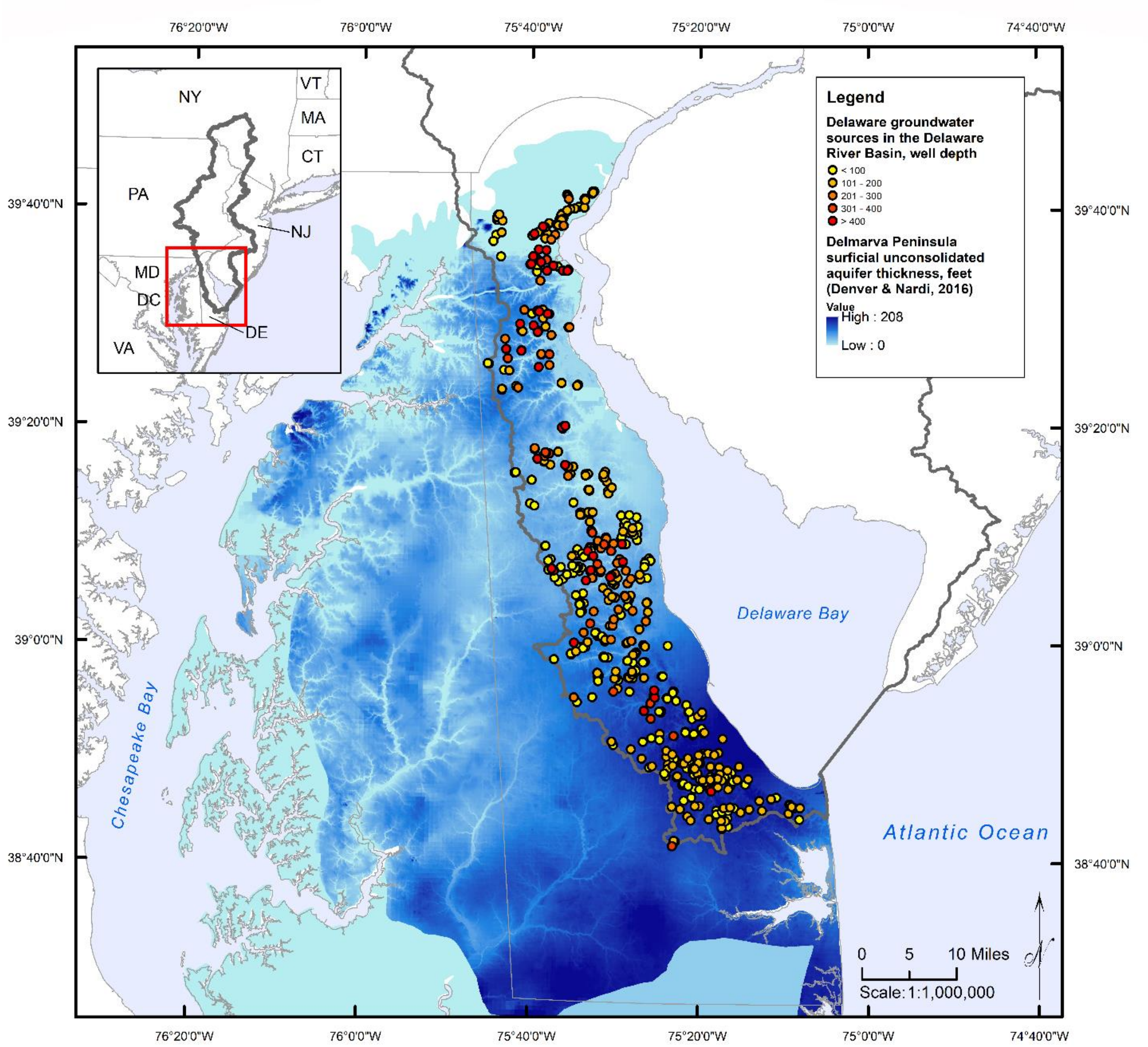


Figure 25: *Groundwater withdrawals from the Coastal Plain in Delaware, color coded by the installation depth, plotted over spatial data indicating the thickness of the surficial unconfined aquifer (Denver & Nardi, 2016). From this comparison, it is possible to classify those wells which are assumed to be installed in the unconfined aquifer (presented in Figure 24).*

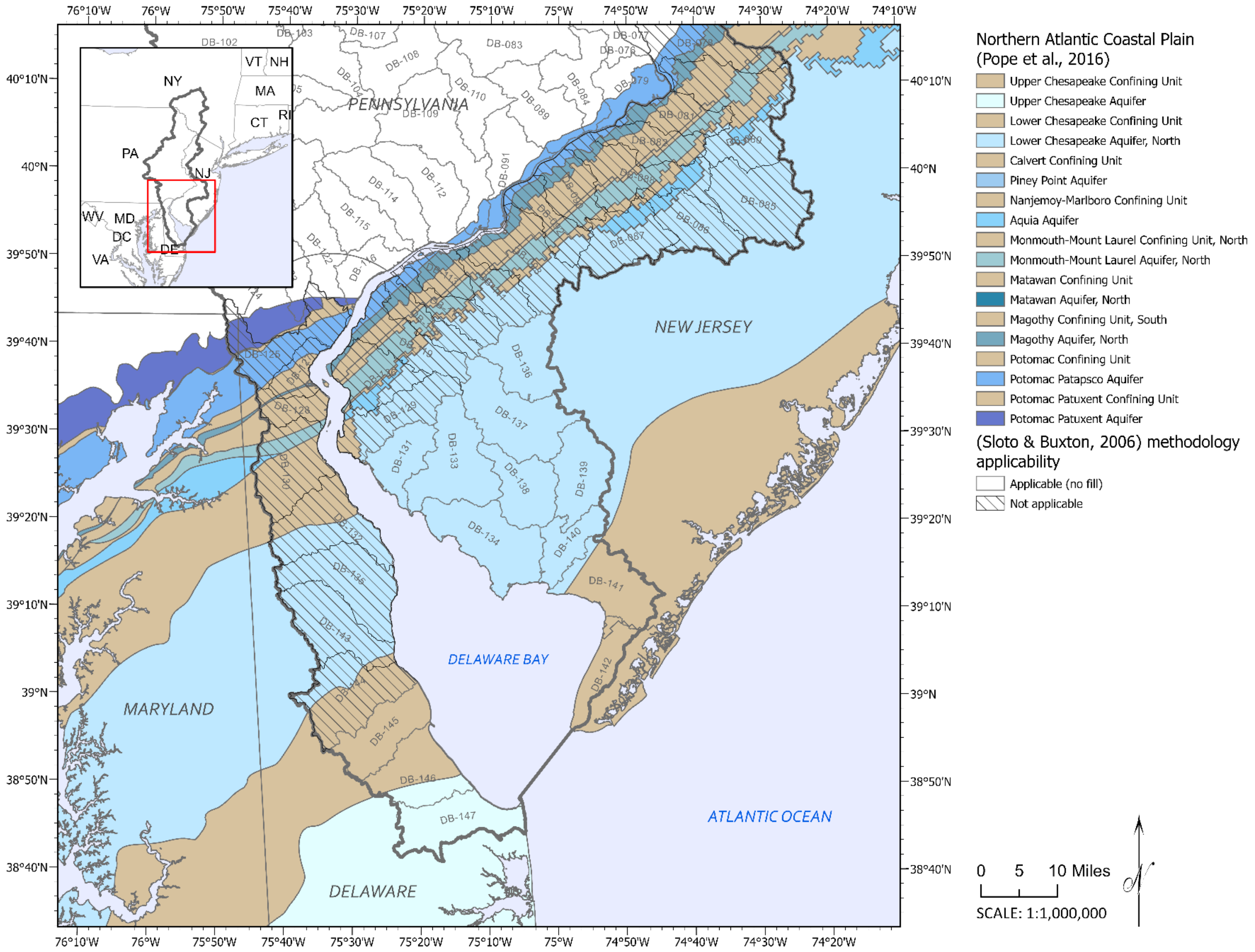


Figure 26: *Indication of which of the 147 subbasins meet assumptions in Sloto & Buxton, 2006 to apply the groundwater availability screening methodology. The subbasins are overlaying the regional hydrogeologic units in the North Atlantic Coastal Plain Aquifer as presented in Pope et al., 2016, corresponding to Figure 24.*

5.1.4.3. Ongoing groundwater availability efforts in the Coastal Plain

This study concluded that the methodology developed in Sloto & Buxton, 2006 is not appropriate for twenty-six subbasins in the Coastal Plain because the majority of groundwater withdrawals in these subbasins are from the underlying confined aquifer network. However, DRBC is not the only agency assessing groundwater availability in this region, nor is the methodology developed in Sloto & Buxton, 2006 the only potential tool. This section summarizes some ongoing work within the Coastal Plain portion of the Delaware River Basin. It is advisable that readers reference specific primary sources as cited for full details pertaining to each item below.

(1) **<u>New Jersey: unconfined aquifers and non-reservoir surface water</u>**. This methodology was discussed and summarized in Section 2.4 of this report.

(2) **<u>New Jersey: Coastal Plain confined aquifers</u>**. NJDEP has two designated areas of critical water supply concern which are focused on the confined aquifer network within the Coastal Plain:

   1. **Critical Area I** was designated on July 20, 1985 by administrative order (NJAC 7:19-8.4). This area includes four aquifers: the Mt. Laurel-Wenonah, the Englishtown, the Old Bridge, and the Farrington with extents based on findings from (Eckel & Walker, 1986). This area is located outside of the Delaware River Basin. The New Jersey Water Supply Plan 2017–2022 provides updates on the status of this program and references additional information (Spitz et al., 2007; Spitz, 2009).
   2. **Critical Area II** was designated on July 20, 1993 by administrative order (NJAC 7:19-8.5). This area includes the PRM aquifer system, with extents based on findings from Eckel & Walker, 1986. As shown in Figure 2, this area overlaps with the Delaware River Basin. The designation of Critical Area II required reductions in withdrawals from the PRM aquifer system within the delineated area, which began in 1993. The New Jersey Water Supply Plan 2017–2022 provides updates on the status of this program and references additional information (Spitz & dePaul, 2008).

(3) **<u>New Jersey: Pinelands Commission and the Kirkwood-Cohansey aquifer</u>**. In addition to regulatory approvals required through regulations for Water Supply Allocation Permits (NJAC 7:19), the Pinelands Protection Act of 1979 (N.J.S.A. 13:18A-1 et. seq.) serves as the authority for the Pinelands Comprehensive Management Plan (NJAC 7:50). This plan provides protection and preservation measures for the New Jersey Pinelands, including NJAC 7:50-6.86 (Water Management) which outlines groundwater withdrawal requirements. One example regulation requires that non-agricultural withdrawals from the Kirkwood-Cohansey aquifer only be permitted if it is demonstrated that the proposed use will not result in any “adverse ecological impact” on the Pinelands Area.

More recently, the New Jersey Legislature enacted NJ, P.L. 2001 c. 165 pertaining to water supply in the Pinelands and Cape May County. The portion of this legislation related to the Kirkwood-Cohansey aquifer, outlined in Section 1, is to “*assess and prepare a report on the key hydrologic and ecological information necessary to determine how the current and future water supply needs within the Pinelands area may be met while protecting the Kirkwood-Cohansey aquifer system and while avoiding any adverse ecological impact on the pinelands area.*” As a result, a work plan for the Kirkwood-Cohansey Project was approved by the Pinelands Commission in 2003 (Pinelands, 2003), setting forth a course of action to determine how current and future water demands might be met while protecting natural resources (e.g., avoid lowering of water levels in ponds/wetlands due to groundwater withdrawals). Three drainage basins within the Pinelands were selected (from a pool of 39 candidates) for a suite of hydrology and wetland ecology studies because they represent a range of typical hydrologic, geologic, and ecological conditions and landscape features: the

Albertson Brook, McDonalds Branch, and Morses Mill Stream drainage basins; the McDonalds Branch of Rancocas Creek is within the Delaware River Basin (Walker et al., 2008). Examples of these studies include the development of a hydrologic-framework model (Walker et al., 2008), a study evaluating groundwater–surface water interactions (Walker et al., 2011), a study specific to evapotranspiration (Sumner et al., 2012), and the development of three-dimensional groundwater flow models (Emmanuel & Nicholson, 2012).

(4) **New Jersey: Coastal Plain in Cape May County**. The New Jersey Legislature enacted NJ, P.L. 2001 c. 165, 2001 pertaining to water supply of the Pinelands and Cape May County. The portion of this legislation pertaining to Cape May County, outlined in Section 3, is "*to assess and prepare a report on sustainable water supply alternatives within Cape May County, but outside of the pinelands area, necessary to meet the current and future water supply needs of Cape May County while avoiding any adverse ground water or ecological impact on Cape May County.*" Studies have been conducted to evaluate stresses on aquifer systems (e.g., saltwater intrusion) and water-dependent ecological resources. A final report was published (Lacombe et al., 2009), and other studies continue to assess water resources (Carleton, 2021).

(5) **Delaware: Groundwater monitoring network and salinity intrusion**. Saltwater intrusion is the salinization of fresh groundwater and is primarily an issue where fresh groundwater is relied upon for water supply; unfortunately, saltwater intrusion is often exacerbated by groundwater withdrawals. The Delaware Department of Natural Resources and Environmental Control (DNREC) and DGS have been performing extensive groundwater monitoring for decades. More specifically, the Delaware Comprehensive State Groundwater Protection Program highlights that one of the non-regulatory programs in place for groundwater protection is *"saltwater intrusion monitoring"* (DNREC, 1999). Some highlights regarding Delaware's groundwater monitoring and saltwater intrusion prevention efforts are:

1. DNREC's Division of Water has continuing monitoring efforts geared specifically towards saltwater intrusion in each of Delaware's counties, such as a statewide saltwater buffer around every tidal water body to help safeguard constructed wells against saltwater impacts (DNREC, 2021). A summary of findings from this article are presented below:
    i. **New Castle County**: DNREC Division of Water has monitored several wells in the Potomac aquifer since the 1970s, and current water quality results do not indicate that saltwater intrusion poses an issue.
    ii. **Kent County**: Due to high salinity in freshwater, DNREC Division of Water has installed a network of monitoring wells in five different aquifers in the Town of Bowers (some to be used for water supply, all to be monitored as part of the Delaware Groundwater Monitoring Network).
    iii. **Sussex County**: DNREC Division of Water monitors several wells located along the Route 1 corridor between Rehoboth Beach and Fenwick Island; the data show stable salt levels in the monitored aquifers. Additional work is being performed with coastal communities to monitor groundwater supplies more closely for early detection of salinization.
2. The Coastal Sussex County Groundwater Monitoring Network was established by DNREC and DGS in 1987 for the purpose of monitoring for saltwater intrusion and was maintained by DGS (DNREC, 1999). The Potomac Sampling Monitor Well Network was established by the USGS in the 1970s, and has since been used by DNREC to monitor saltwater intrusion (DNREC, 1999). The current Delaware Groundwater Monitoring Network is maintained by DGS, with the number of wells fluctuating based on staff and funding (DGS, 2021). DGS

recently completed two projects at the request of the Delaware Water Supply Coordinating Council, aimed at filling gaps in the existing groundwater monitoring infrastructure network.

i. **Southern New Castle County, Northern Kent County**: This work was published as *Report of Investigations No. 82* (S. A. Andres et al., 2018). In 2012, DGS began a multi-year project to install new monitoring infrastructure to address many of the geologic, hydraulic, and hydrologic information gaps identified by previous USACE and DGS studies (Dugan et al., 2008; He & Andres, 2011; USACE, 2006). Closing these monitoring network gaps is intended to provide data to support decision making and applied research on a variety of current and future water quantity and quality issues. This study focused on shallower aquifers that provide baseflow to streams and are commonly used for domestic, public water supply, irrigation, and commercial purposes (Columbia, Rancocas, Mt. Laurel, and Magothy aquifers). The study required installation of 26 wells, utilization of 24 existing wells, and data from four USGS stream gages (two of which were reactivated for the study).

ii. **Kent County:** This work was published as *Open File Report No. 53* (S. Andres et al., 2019). In 2017, DGS began a multi-year project to install new monitoring infrastructure to address spatial gaps in monitoring infrastructure and water-resource data identified through previous DGS research conducted in Kent County. This study focused on aquifers in Kent County that provide baseflow to streams and are used for domestic, public water supply, irrigation, and commercial purposes (Columbia, Milford, Frederica, Federalsburg, Cheswold, Piney Point, Rancocas, and Mt. Laurel aquifers). At ten sites, multiple wells were installed in different aquifers; however, not every site has wells in each aquifer. A total 42 of wells were installed. Studies such as slug tests and pump tests were performed to calculate pertinent hydraulic characteristics of different aquifers, such as hydraulic conductivity and transmissivity. Geophysical logging allowed for a comparison of observed aquifer top/bottom elevations against calculations from digital elevation maps.

5.1.4.4. Projected withdrawals

Generally, there is an increasing trend in the projected withdrawals among the grayed-out subbasins. Looking closely, most increases in projected net withdrawals come from Delaware, while in New Jersey the withdrawals appear steady with a slight decreasing trend (**Table 3**). The greatest decreases in projected net withdrawals are in DB-082 (-32%) and DB-085 (-33%). The greatest increases in withdrawals are in subbasins DB-081 (+19%) and DB-130 (+100%). A further look into the sector specific projections from Thompson & Pindar, 2021 suggests that most changes in the projected withdrawals are due to changes in public water supply withdrawals.

5.2. Southeastern Pennsylvania Groundwater Protected Area

5.2.1. 25-year Recurrence interval baseflow

Considering RI-25 baseflows, groundwater availability calculations for 2020 and 2060 using projected net withdrawals and the 95%PI withdrawals are presented for the SEPA-GWPA in Figure 27 and Table 4. The screening tool revealed that subbasin SP-03 is at risk of exceeding withdrawal limits and SP-29 exceeds withdrawal limits; more detailed assessments were performed for SP-03 (Section 5.2.3.1) and SP-29 (Section 5.2.3.2), and SP-29. With projected net withdrawals for RI-25 baseflow, percent groundwater use in subbasin SP-03 is expected to increase from 72% to 81% of available RI-25 baseflow between 2020 and 2060 (Table 4). Between 2020 and 2060, net groundwater withdrawal is expected to decrease in SP-20, -31, -50, -59 and -73. Considering 95%PI net withdrawal, several subbasins exceed 50% use of available groundwater.

5.2.2. 50-year Recurrence interval baseflow

Considering RI-50 baseflows, groundwater availability calculations for 2020 and 2060 using projected net withdrawals and the 95%PI withdrawals are presented for the SEPA-GWPA in Figure 28 and Table 4. Between 2020 and 2060, no subbasin is projected to change in screening threshold category with projected net withdrawals, though there are some changes within screening categories. For example, in SP-03, groundwater use is projected to increase from 85% to 96% of available RI-50 baseflow between 2020 and 2060. The 95%PI net withdrawals show significantly less groundwater availability across the SEPA-GWPA area compared with the projected net withdrawals. In this 95%PI scenario, subbasins SP-03 and SP-29 exceed groundwater availability (95%PI withdrawal is >100% of the RI-50 baseflow) while net withdrawals from subbasins SP-58 and SP-61 increase to use >75% of available groundwater (Figure 28). In SP-61, groundwater net withdrawal increases from 64% (projected net withdrawals in 2060) to 78% (95%PI net withdrawals in 2016) (Table 4). Further investigation into subbasins which approach or exceed their respective withdrawal limits may include alternative source evaluation, conjunctive source evaluation, or other alternatives as outlined in the SEPA-GWPA regulations. These processes can help maintain groundwater supply in potentially stressed watersheds.

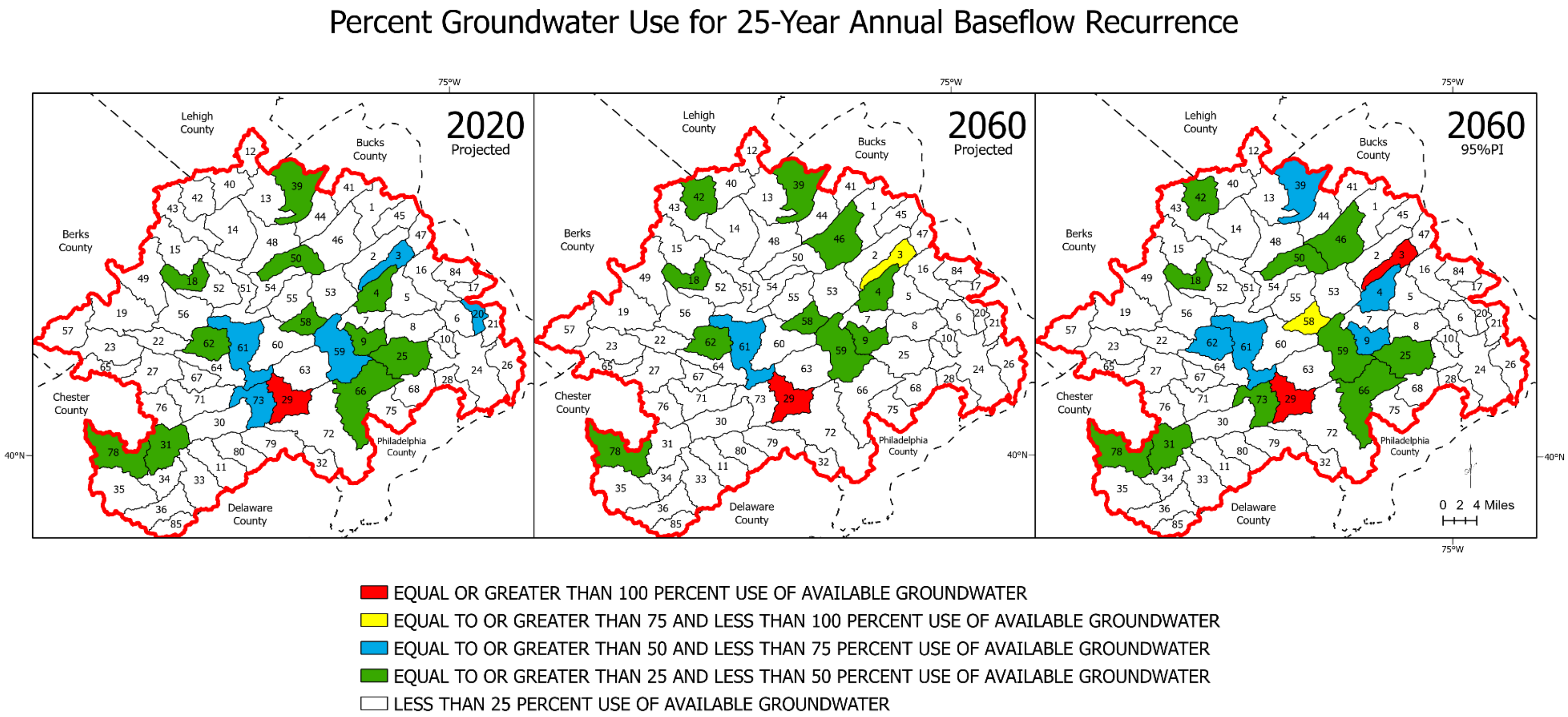


Figure 27: *Groundwater availability in each SEPA-GWPA subbasin in 2020 and 2060, considering the 1-in-25-year baseflow and using projected (left and center panels) and 95%PI (right panel) net withdrawal values. The SEPA-GWPA boundary is represented by the solid red outline.*

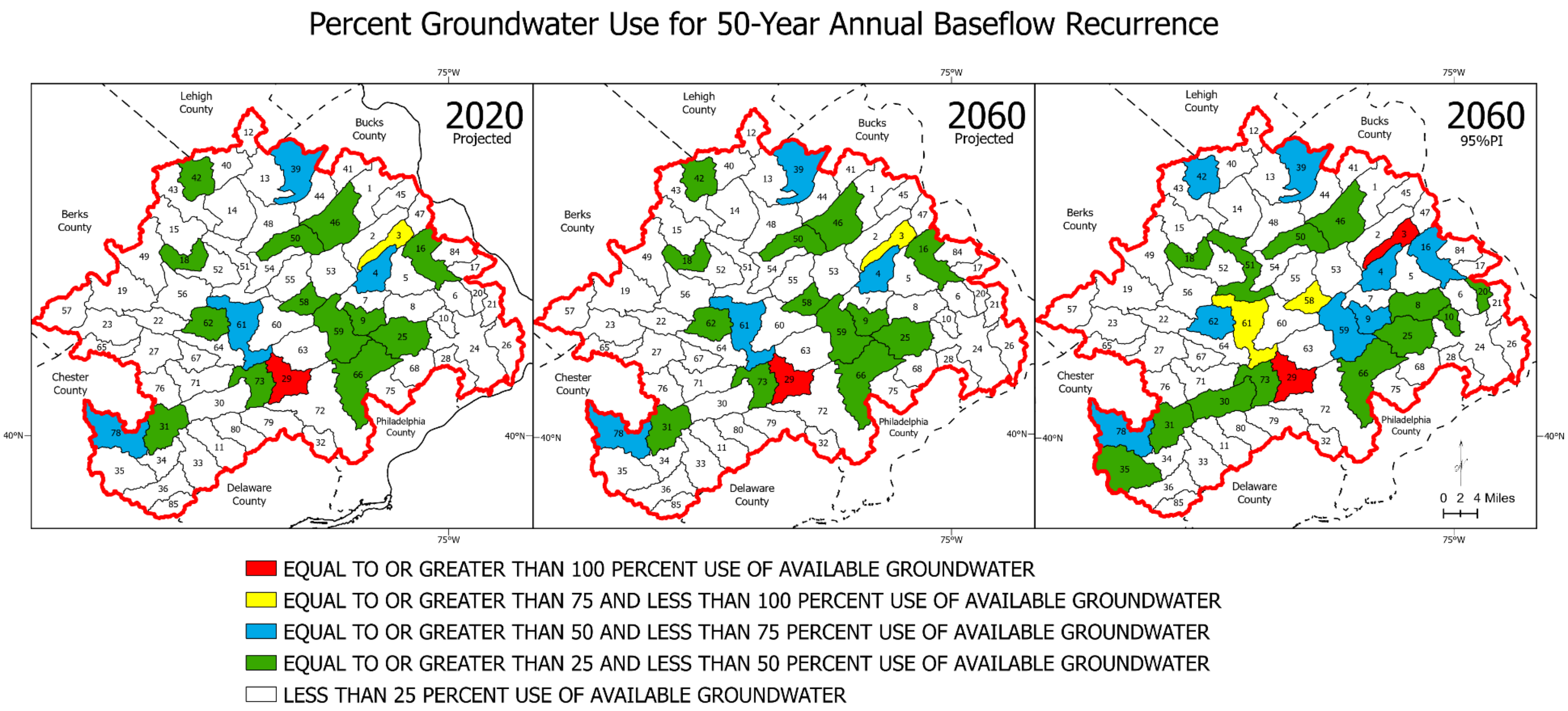


Figure 28: *Groundwater availability in each SEPA-GWPA subbasin in 2020 and 2060, considering the 1-in-50-year baseflow and using projected (left and center panels) and 95%PI (right panel) net withdrawal values. The SEPA-GWPA boundary is represented by the solid red outline.*

Table 4: *Projected net and 95%PI net groundwater withdrawals within the SEPA-GWPA presented as a percentage of 25-year and 50-year recurrence interval baseflows. The data in this table correspond with Figure 27 & Figure 28.*

Subbasin ID	Subbasin name (abbreviated)	RI-25 baseflow (MGY)	RI-50 baseflow (MGY)	Net projected values						Upper 95% predictive interval					
				Net GW (MGY)		Percent RI25		Percent RI50		Net GW (MGY)		Percent RI25		Percent RI50	
				2020	2060	2020	2060	2020	2060	2020	2060	2020	2060	2020	2060
SP-1	Tohickon-Deep Run	1,274	1,192	131	173	10%	14%	11%	15%	151	205	12%	16%	13%	17%
SP-2	North Branch Neshaminy Creek	1,131	1,058	155	137	14%	12%	15%	13%	227	223	20%	20%	21%	21%
SP-3	Pine Run Basin	792	668	568	640	72%	81%	85%	96%	787	874	99%	110%	118%	131%
SP-4	Doylestown Subbasin Neshaminy Creek	1,106	887	439	462	40%	42%	49%	52%	615	651	56%	59%	69%	73%
SP-5	Warwick Subbasin Neshaminy Creek	1,181	1,044	139	143	12%	12%	13%	14%	205	219	17%	19%	20%	21%
SP-6	Northampton Subbasin Neshaminy Creek	807	710	48	53	6%	7%	7%	7%	79	118	10%	15%	11%	17%
SP-7	Warrington Subbasin Little Neshaminy Creek	676	617	2	2	0%	0%	0%	0%	14	14	2%	2%	2%	2%
SP-8	Warminster Subbasin Little Neshaminy Creek	1,350	1,135	81	84	6%	6%	7%	7%	273	305	20%	23%	24%	27%
SP-9	Park Creek Basin	776	665	232	274	30%	35%	35%	41%	353	407	46%	52%	53%	61%
SP-10	Ironworks Creek Basin	435	366	74	74	17%	17%	20%	20%	83	107	19%	25%	23%	29%
SP-11	Upper Reach Ridley Creek	2,275	1,568	59	45	3%	2%	4%	3%	91	77	4%	3%	6%	5%
SP-12	Upper Reach Saucon Creek	1,261	1,053	15	17	1%	1%	1%	2%	21	25	2%	2%	2%	2%
SP-13	Unami-Licking Creeks	1,323	1,237	138	169	10%	13%	11%	14%	190	223	14%	17%	15%	18%
SP-14	Perkiomen-Macoby Creek	1,669	1,561	225	287	13%	17%	14%	18%	306	372	18%	22%	20%	24%
SP-15	Swamp-Middle Creeks	1,896	1,533	100	180	5%	9%	6%	12%	148	239	8%	13%	10%	16%
SP-16	Mill Creek Basin	1,565	439	172	203	11%	13%	39%	46%	230	265	15%	17%	52%	60%
SP-17	Jericho Creek	562	510	9	8	2%	1%	2%	2%	9	8	2%	1%	2%	2%
SP-18	Swamp-Minister Creeks	729	678	195	221	27%	30%	29%	33%	240	267	33%	37%	35%	39%
SP-19	Schuylkill-Sixpenny Creek	1,987	1,736	137	148	7%	7%	8%	9%	182	210	9%	11%	10%	12%
SP-20	Newtown Creek	397	346	228	84	57%	21%	66%	24%	246	96	62%	24%	71%	28%
SP-21	Core Creek Basin	658	555	4	2	1%	0%	1%	0%	7	5	1%	1%	1%	1%
SP-22	Pigeon Creek	815	762	51	54	6%	7%	7%	7%	62	74	8%	9%	8%	10%
SP-23	Upper Reach French Creek	1,726	1,403	21	19	1%	1%	1%	1%	36	33	2%	2%	3%	2%
SP-24	Lower Section Subbasin Neshaminy Creek	4,027	2,933	91	57	2%	1%	3%	2%	128	121	3%	3%	4%	4%
SP-25	Upper Reach Pennypack Creek	1,811	1,442	554	442	31%	24%	38%	31%	825	713	46%	39%	57%	49%
SP-26	Mill Creek	2,134	1,514	29	29	1%	1%	2%	2%	38	57	2%	3%	2%	4%
SP-27	Middle Reach French Creek	2,145	1,546	36	44	2%	2%	2%	3%	45	62	2%	3%	3%	4%
SP-28	Upper Reach Poquessing Creek	1,345	940	6	9	0%	1%	1%	1%	10	14	1%	1%	1%	2%
SP-29	Schuylkill-Crow Creek	1,542	1,291	2690	2685	174%	174%	208%	208%	3339	4070	216%	264%	259%	315%
SP-30	Valley Creek	2,487	2,154	296	304	12%	12%	14%	14%	494	570	20%	23%	23%	26%
SP-31	West Valley Creek	2,230	1,725	643	473	29%	21%	37%	27%	795	648	36%	29%	46%	38%
SP-32	Upper Reach Cobbs Creek	1,161	801	0	0	0%	0% %	0%	0%	0	0	0%	0%	0%	0%
SP-33	Upper Reach East Branch Chester Creek	2,486	1,713	12	10	0%	0%	1%	1%	26	12	1%	1%	2%	1%
SP-34	East Branch Brandywine-Taylor Run	1,406	973	19	3	1%	0%	2%	0%	37	5	3%	0%	4%	0%
SP-35	West Branch Brandywine-Broad Run	3,174	2,187	253	452	8%	14%	12%	21%	404	636	13%	20%	18%	29%
SP-36	Upper Reach Brandywine Creek	2,153	1,483	14	14	1%	1%	1%	1%	19	20	1%	1%	1%	1%
SP-39	Tohickon-Beaver-Morgan Creeks	1,540	1,440	731	770	47%	50%	51%	53%	868	912	56%	59%	60%	63%
SP-40	Hosensack-Indian Creeks	1,675	1,230	14	19	1%	1%	1%	2%	15	20	1%	1%	1%	2%
SP-41	Tohickon-Lake Nockamixon	741	693	4	3	1%	0%	1%	0%	4	3	1%	0%	1%	0%
SP-42	Upper Reach Perkiomen Creek	1,632	1,181	367	488	22%	30%	31%	41%	487	619	30%	38%	41%	52%
SP-43	West Branch Perkiomen Creek	1,801	1,444	113	111	6%	6%	8%	8%	180	317	10%	18%	12%	22%

Table 5 (continued): *Projected net and 95%PI net groundwater withdrawals within the SEPA-GWPA presented as a percentage of 25-year and 50-year recurrence interval baseflows. The data in this table correspond with Figure 27 & Figure 28.*

Subbasin ID	Subbasin Name	RI-25 baseflow (MGY)	RI-50 baseflow (MGY)	Net projected values						Upper 95% predictive interval					
				Net GW (MGY)		Percent RI25		Percent RI50		Net GW (MGY)		Percent RI25		Percent RI50	
				2020	2060	2020	2060	2020	2060	2020	2060	2020	2060	2020	2060
SP-44	Tohickon-Three Mile Run	968	906	165	164	17%	17%	18%	18%	215	224	22%	23%	24%	25%
SP-45	Tohickon-Geddes-Cabin Runs	804	752	70	81	9%	10%	9%	11%	90	101	11%	13%	12%	13%
SP-46	East Branch Perkiomen-Morris Run	1,619	1,514	388	539	24%	33%	26%	36%	543	720	34%	44%	36%	48%
SP-47	Paunnacussing Creek	683	587	7	6	1%	1%	1%	1%	7	6	1%	1%	1%	1%
SP-48	Unami-Ridge Valley Creeks	1,425	1,332	29	29	2%	2%	2%	2%	37	41	3%	3%	3%	3%
SP-49	Lower Reach Manatawny-Ironstone Creek	2,416	1,969	133	135	6%	6%	7%	7%	152	166	6%	7%	8%	8%
SP-50	East Branch Perkiomen-Mill Creeks	961	899	260	232	27%	24%	29%	26%	336	288	35%	30%	37%	32%
SP-51	Perkiomen-Deep Creeks	1,396	1,305	259	236	19%	17%	20%	18%	341	327	24%	23%	26%	25%
SP-52	Swamp-Scioto Creeks	994	930	94	93	9%	9%	10%	10%	114	120	11%	12%	12%	13%
SP-53	West Branch Neshaminy Creek Basin	1,402	1,311	36	20	3%	1%	3%	2%	146	39	10%	3%	11%	3%
SP-54	East Branch Perkiomen-Indian Creeks	844	789	136	105	16%	12%	17%	13%	222	196	26%	23%	28%	25%
SP-55	Upper Reach Skippack Creek	1,084	1,014	179	216	17%	20%	18%	21%	263	246	24%	23%	26%	24%
SP-56	Schuylkill-Sprogels Run	1,455	1,360	179	181	12%	12%	13%	13%	275	316	19%	22%	20%	23%
SP-57	Hay Creek	1,299	1,186	14	14	1%	1%	1%	1%	22	48	2%	4%	2%	4%
SP-58	Towamencin Creek	622	582	279	288	45%	46%	48%	50%	443	476	71%	77%	76%	82%
SP-59	Upper Reach Wissahickon Creek	1,737	1,526	894	535	51%	31%	59%	35%	1215	796	70%	46%	80%	52%
SP-60	Lower Reach Skippack Creek	1,427	1,334	90	78	6%	5%	7%	6%	149	125	10%	9%	11%	9%
SP-61	Perkiomen-Lodal Creeks	1,600	1,478	834	946	52%	59%	56%	64%	1017	1150	64%	72%	69%	78%
SP-62	Schuylkill-Mingo Creek	895	837	314	304	35%	34%	37%	36%	415	458	46%	51%	50%	55%
SP-63	Stony Creek	1,655	1,424	71	69	4%	4%	5%	5%	97	94	6%	6%	7%	7%
SP-64	Schuylkill-Stony Creek	915	825	29	30	3%	3%	4%	4%	36	46	4%	5%	4%	6%
SP-65	South Branch French Creek	1,391	981	13	13	1%	1%	1%	1%	16	19	1%	1%	2%	2%
SP-66	Lower Reach Wissahickon Creek	3,667	2,836	1425	819	39%	22%	50%	29%	1757	1251	48%	34%	62%	44%
SP-67	Lower Reach French Creek	843	677	73	74	9%	9%	11%	11%	115	136	14%	16%	17%	20%
SP-68	Middle Reach Pennypack Creek	1,727	1,202	0	0	0%	0%	0%	0%	0	0	0%	0%	0%	0%
SP-71	Lower Reach Pickering Creek	2,286	1,613	27	28	1%	1%	2%	2%	51	58	2%	3%	3%	4%
SP-72	Schuylkill-Plymouth-Mill Creeks	5,929	4,270	16	16	0%	0%	0%	0%	31	31	1%	1%	1%	1%
SP-73	Schuylkill-Trout Creek	1,444	1,189	746	367	52%	25%	63%	31%	1015	585	70%	41%	85%	49%
SP-75	Upper Reach Frankford Creek	1,886	1,299	65	91	3%	5%	5%	7%	83	113	4%	6%	6%	9%
SP-76	Upper Reach Pickering Creek	1,812	1,248	8	7	0%	0%	1%	1%	9	8	0%	0%	1%	1%
SP-78	West Branch Brandywine-Beaver Run	2,814	2,130	844	1081	30%	38%	40%	51%	995	1245	35%	44%	47%	58%
SP-79	Upper Reach Darby Creek	2,167	1,493	21	21	1%	1%	1%	1%	49	49	2%	2%	3%	3%
SP-80	Upper Reach Crum Creek	1,721	1,190	20	20	1%	1%	2%	2%	41	42	2%	2%	3%	3%
SP-84	Pidcock Creek	751	686	5	5	1%	1%	1%	1%	5	5	1%	1%	1%	1%
SP-85	Middle Reach Brandywine Creek	1,098	756	5	6	0%	1%	1%	1%	5	6	0%	1%	1%	1%

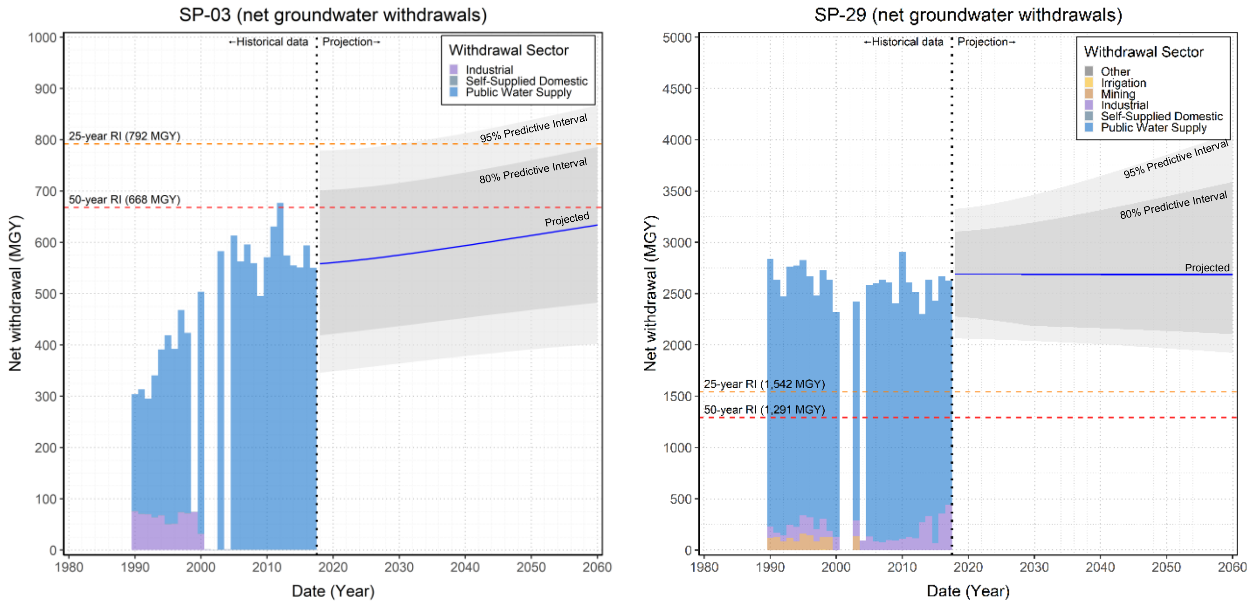


__Figure 29:__ Historical and projected net groundwater withdrawals from subbasins within the SEPA-GWPA which have projected withdrawals or predictive intervals that meet or exceed the 50-year recurrence interval (as indicated in Table 4). These withdrawals are based on data provided by Thompson & Pindar, 2021, color coded by withdrawal sector.

5.2.3. Screening tool assessment

Two SEPA-GWPA subbasins show a possibility for net groundwater withdrawal above the RI-25 and RI-50 baseflows: SP-03 (Pine Run in the Neshaminy Creek headwaters) and SP-29 (Crow Creek in the Schuylkill River watershed). Time series of historic net groundwater withdrawals in these two subbasins are presented in Figure 29, along with the corresponding projection and predictive intervals through 2060. The withdrawal characteristics of each subbasin vary though public water supply is the dominant sector in both.

5.2.3.1. SP-03: Pine Run (Neshaminy Creek headwaters)

Net groundwater withdrawals from SP-03 are projected to continue increasing through 2060 (Figure 29). Notably, projection uncertainty (predictive intervals with a wide range) causes this subbasin to screen >100% relative to RI-25 and RI-50 baseflows. The industrial groundwater withdrawal was associated with a pigment manufacturing facility that ceased manufacturing operations (and withdrawal) at this location in 2001.

Subbasin SP-03 is located in the headwaters of the Neshaminy Creek on the northern side of the Chalfont Fault (Figure 30) and is underlain predominantly by Stockton Formation which is "*light-gray to buff, coarse-grained, arkosic sandstone includes reddish-brown to grayish-purple sandstone, mudstone, and shale*" (Berg et al., 1980). The Stockton Formation is one of a three main Triassic age sedimentary rock formations in the broader area underlying this portion of northern Bucks County, Pennsylvania; the other two are the Brunswick Group and the Lockatong Formation (Figure 30). The Stockton Formation strikes approximately N 65° E and dips approximately 10° NW as indicated from on Wherry et al., 1931. Two cross-sections from Wherry et al., 1931 have been digitized in Figure 31 and their extents incorporated into Figure 30. Cross-section C-C' transects SP-03 (subbasin extents indicated on the cross-section), which suggests that the Stockton Formation comprises most of the subbasin even at depth.

As described in Sloto & Schreffler, 1994, the Triassic age sedimentary rock groundwater system can be visualized as a series of sedimentary beds with a relatively high transmissivity separated by beds with relatively low transmissivity. Within the high-transmissivity beds, groundwater moves through a network of interconnecting secondary openings such as fractures, bedding planes and joints. The groundwater is unconfined in the shallower part of the aquifer and may be considered confined or semiconfined in the

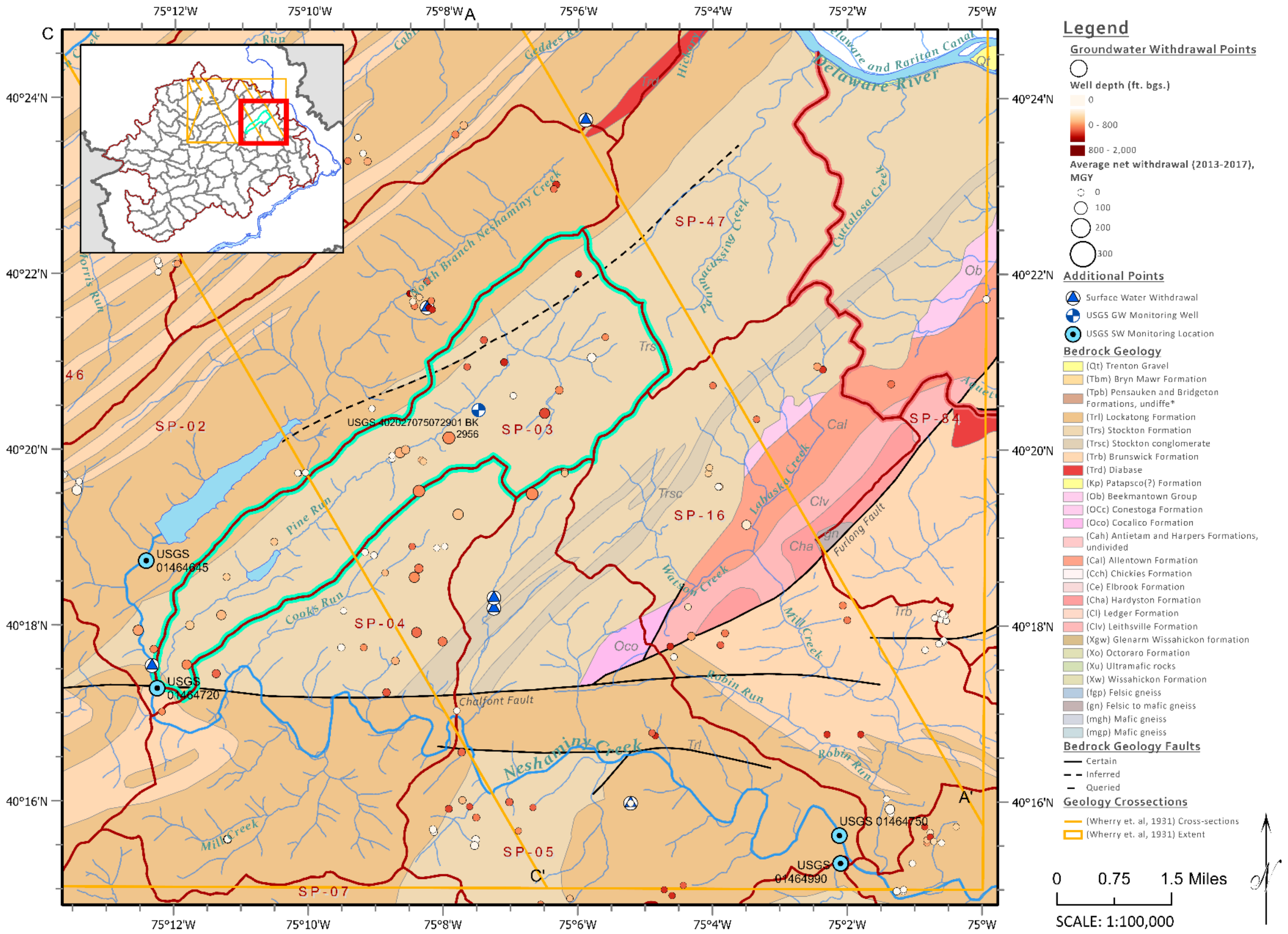


Figure 30: *A map highlighting SEPA-GWPA subbasin SP-03. Extent of analysis and cross sections on a regional scale were adopted from Wherry et al., 1931. Pennsylvania geology and faults were obtained from PA DCNR, 2001 and PA DCNR, 2016, respectively.*

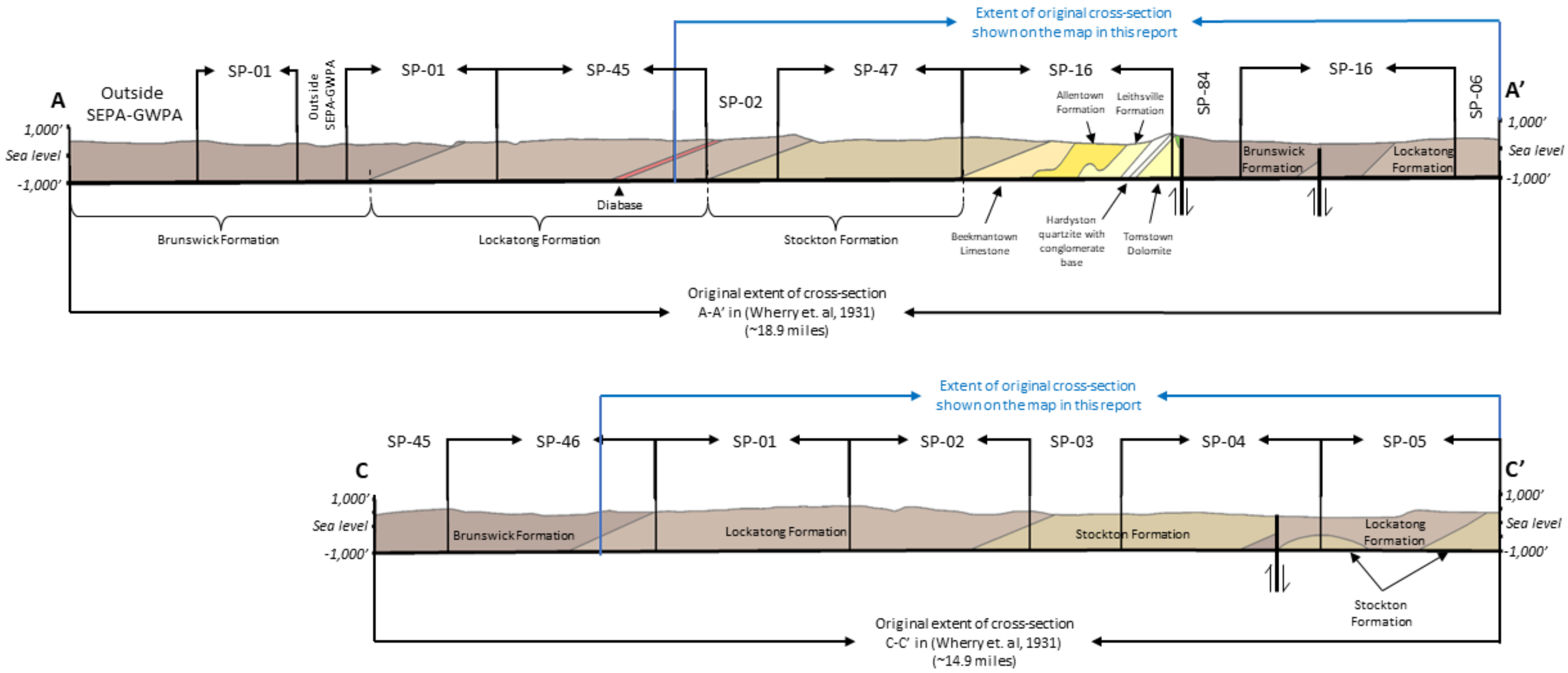


__Figure 31:__ Cross-sections A-A' and C-C', corresponding to Figure 30. The details of this cross-section have been adopted from Wherry et al., 1931.

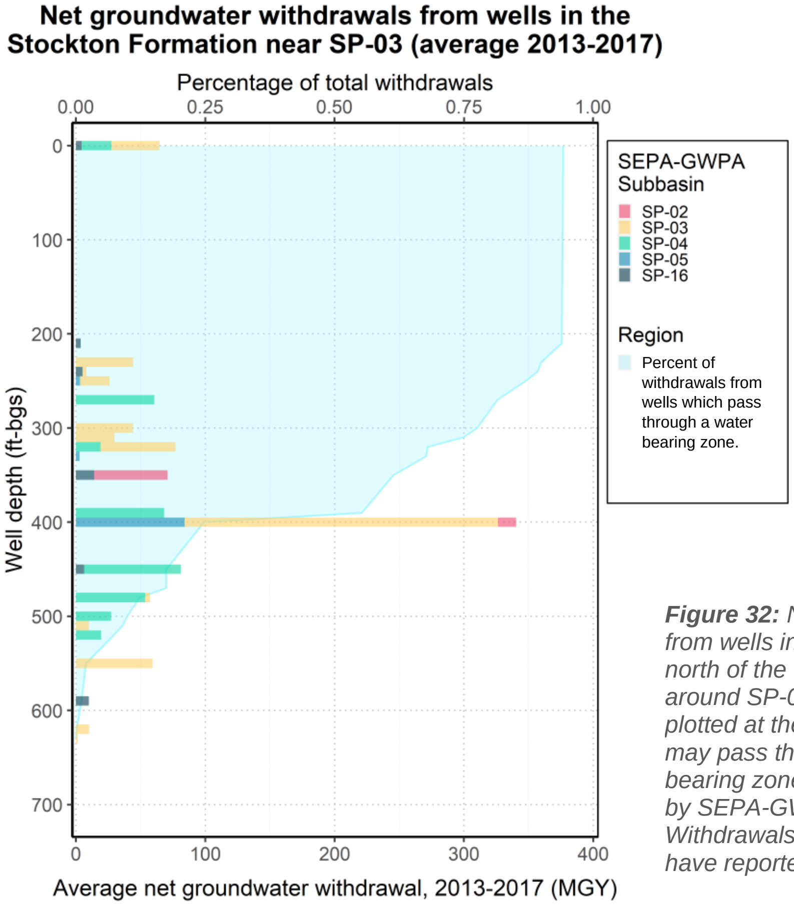


Figure 32: *Net groundwater withdrawals from wells in the Stockton Formation, north of the Chalfont Fault, in and around SP-03. The withdrawals are plotted at the reported well depth but may pass through multiple water bearing zones. The data are color coded by SEPA-GWPA subbasin ID. Withdrawals reported at 0 ft-bgs do not have reported well depths.*

deeper part of the aquifer. Each formation has multiple water-bearing zones which decrease in frequency with depth; about 65% of the water-bearing zones for all hydrogeologic units are within 200 feet of the land surface and 85% are within 300 feet of the land surface. Specifically, the Stockton formation was shown to have about 1.6 water-bearing zones per 100 feet of uncased borehole, which is more than the Brunswick Group and the Lockatong Formation (Sloto & Schreffler, 1994).

Notably, Sloto & Schreffler, 1994 discuss how non-domestic wells generally provide a better measure of maximum aquifer yield than domestic wells because (1) non-domestic wells generally target maximum yield, whereas domestic wells may focus on convenient locations and are only drilled until adequate yield, and (2) nondomestic wells are generally deeper, may be open boreholes, may pass through water-bearing zones and are typically larger in diameter. Based on reported well data compiled by Schreffler et al., 1994 and summarized in Sloto & Schreffler, 1994, the Stockton Formation has higher median non-domestic well yield (120 GPM) than the Brunswick Group (52 GPM) and Lockatong Formation (22 GPM). Therefore, it is likely not a coincidence that SP-03 has a high density of larger withdrawals when compared to immediately adjacent subbasins; furthermore, withdrawals in adjacent subbasins (e.g., SP-04) appear to also be installed in the Stockton Formation Figure 30). Net groundwater withdrawals from the Stockton Formation located north of the Chalfont Fault are plotted according to installed well depth in Figure 32, color coded by the subbasin in which the well is installed (note that withdrawals plotted at 0 ft-bgs do not have reported well depths). These non-domestic wells are typically installed at depths greater than 200 ft-bgs, with about 75% of withdrawals coming from wells installed to a depth of 400 ft-bgs. This trend is consistent with the conclusion in Sloto & Schreffler, 1994 that 85% of the water-bearing zones are within 300 ft of the land surface. Because deeper wells (e.g., 400 ft-bgs) may withdraw water from multiple water-bearing zones

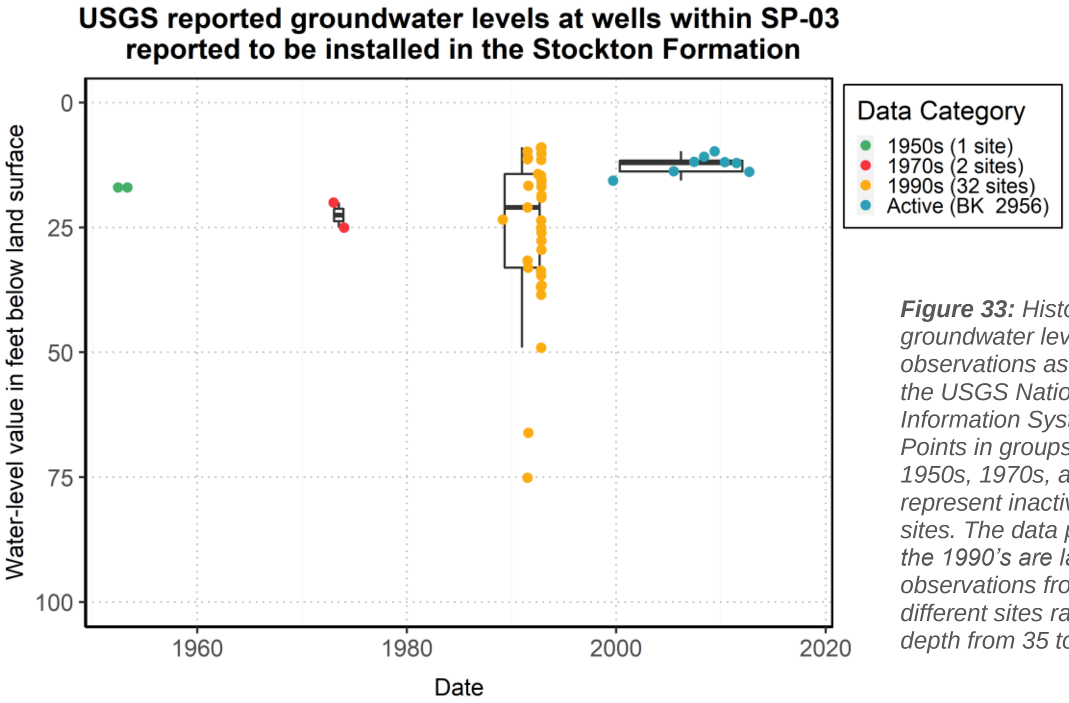


***Figure 33:** Historical groundwater level observations as reported by the USGS National Water Information System (NWIS). Points in groups from the 1950s, 1970s, and 1990s represent inactive monitoring sites. The data presented for the 1990's are largely single observations from 32 different sites ranging in depth from 35 to 320 ft-bgs.*

above the finished depth, it is helpful to consider the blue portion of Figure 32 which indicates the percentage of withdrawals from wells passing through a particular water-bearing zone—meaning that the water-bearing zone may or may not contribute (to some degree) to that portion of overall withdrawals.

Considering the data available regarding the quantity, location and depth of withdrawals from the Stockton Formation around SP-03, it is possible to attempt assessment of the natural environment's response to these human impacts. Groundwater elevations from inactive and active USGS wells within SP-03 are presented in Figure 33. All wells in this figure are said to be installed within the Stockton Formation, at varying depths. The number of sites monitored in each period of time are indicated in the legend; the monitoring campaign in the 1990s consists largely of single observations from 32 sites ranging in depth from 35 to 320 ft-bgs. While the data are limited, they does provide some insight that it is unlikely that groundwater levels have changed much from about 10–25 ft-bgs within this subbasin since the 1950s. Considered with the observed increase in net withdrawals from SP-03 since the 1990s (Figure 29), it is unlikely that the net groundwater withdrawals are adversely affecting *regional* groundwater levels.

5.2.3.2. SP-29: Crow Creek (Schuylkill River watershed)

Net groundwater withdrawals from SP-29 are projected to continue at a relatively constant rate (Figure 29), currently above both RI-25 and RI-50 baseflows. The industrial withdrawals represent a mix of two remediation sites (smaller withdrawals) and a steel plate manufacturing facility (larger production wells). The mining withdrawal is likely ongoing, as it is associated with an active quarry, but does not have readily accessible withdrawal data. The overwhelming majority of the net groundwater withdrawals from SP-29 are for public water supply, namely: (1) a quarry converted to public water supply withdrawal (~2,000 MGY) associated with a 1967 non-expiring DRBC docket and (2) a large production well (~325 MGY) associated with a 1966 non-expiring DRBC docket. Groundwater withdrawals within SP-29 were above the subbasin withdrawal limit prior to the adoption of limits by DRBC in 1999 (Figure 29). To date, the Commission is not aware of any groundwater interference and/or availability issues associated with any groundwater sources subject to Commission review and is not aware of any in-stream impacts attributed to these groundwater withdrawals. Based on this information, no further analysis is recommended for SP-29.

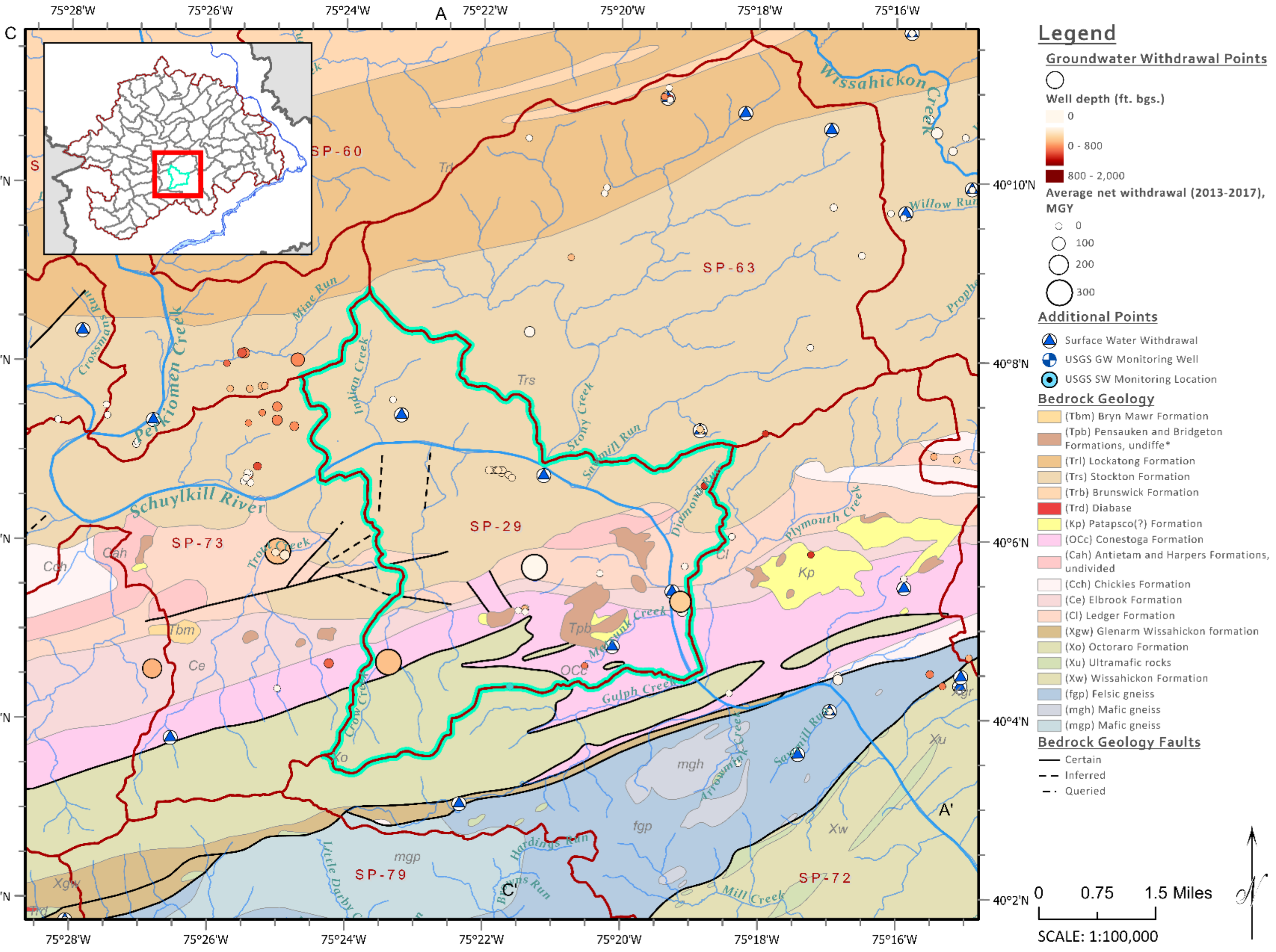
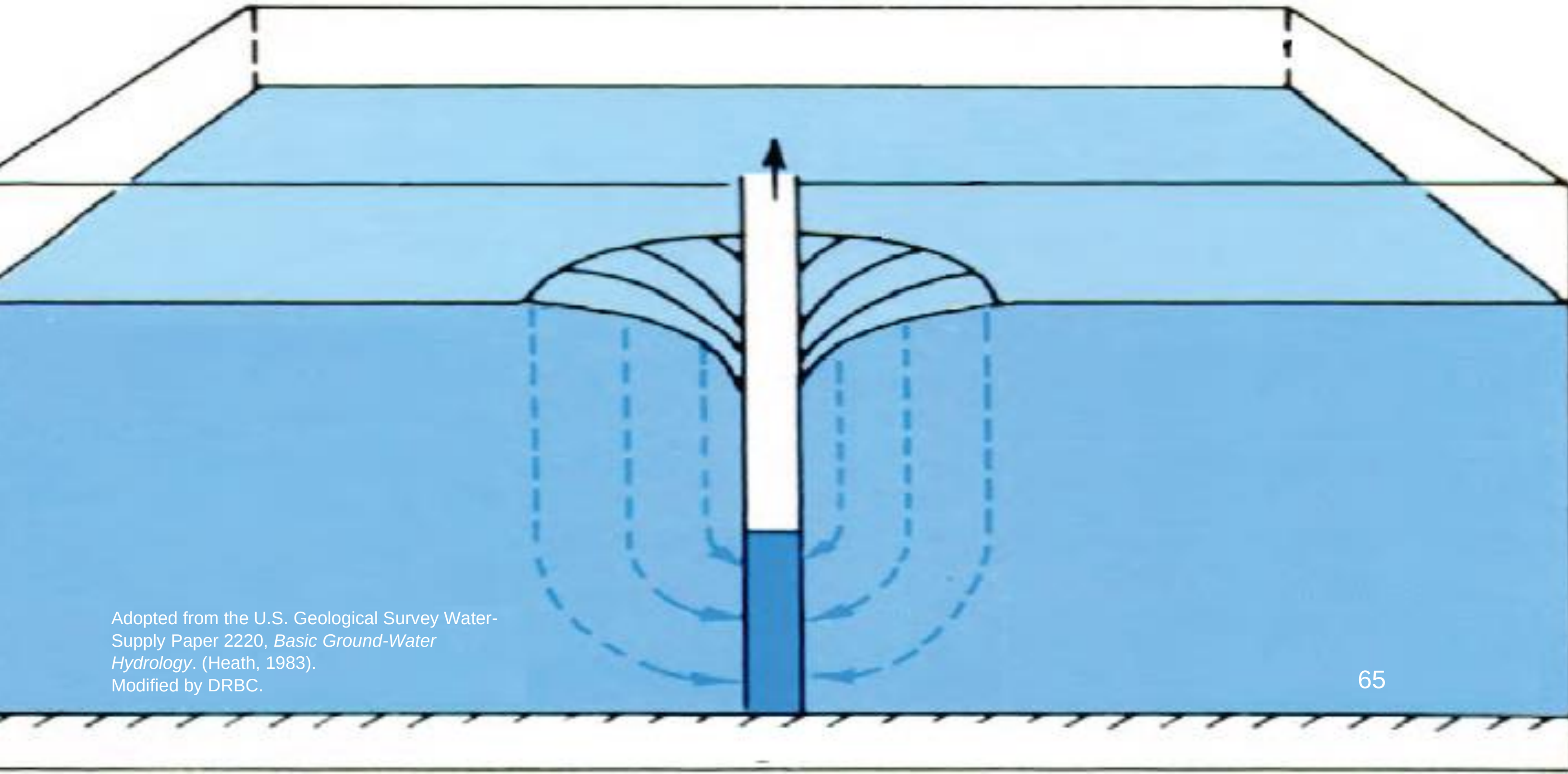


Figure 34: A map highlighting SEPA-GWPA subbasin SP-29. Pennsylvania geology and faults were obtained from PA DCNR, 2001 and PA DCNR, 2016, respectively.



Adopted from the U.S. Geological Survey Water-Supply Paper 2220, *Basic Ground-Water Hydrology*. (Heath, 1983).
Modified by DRBC.

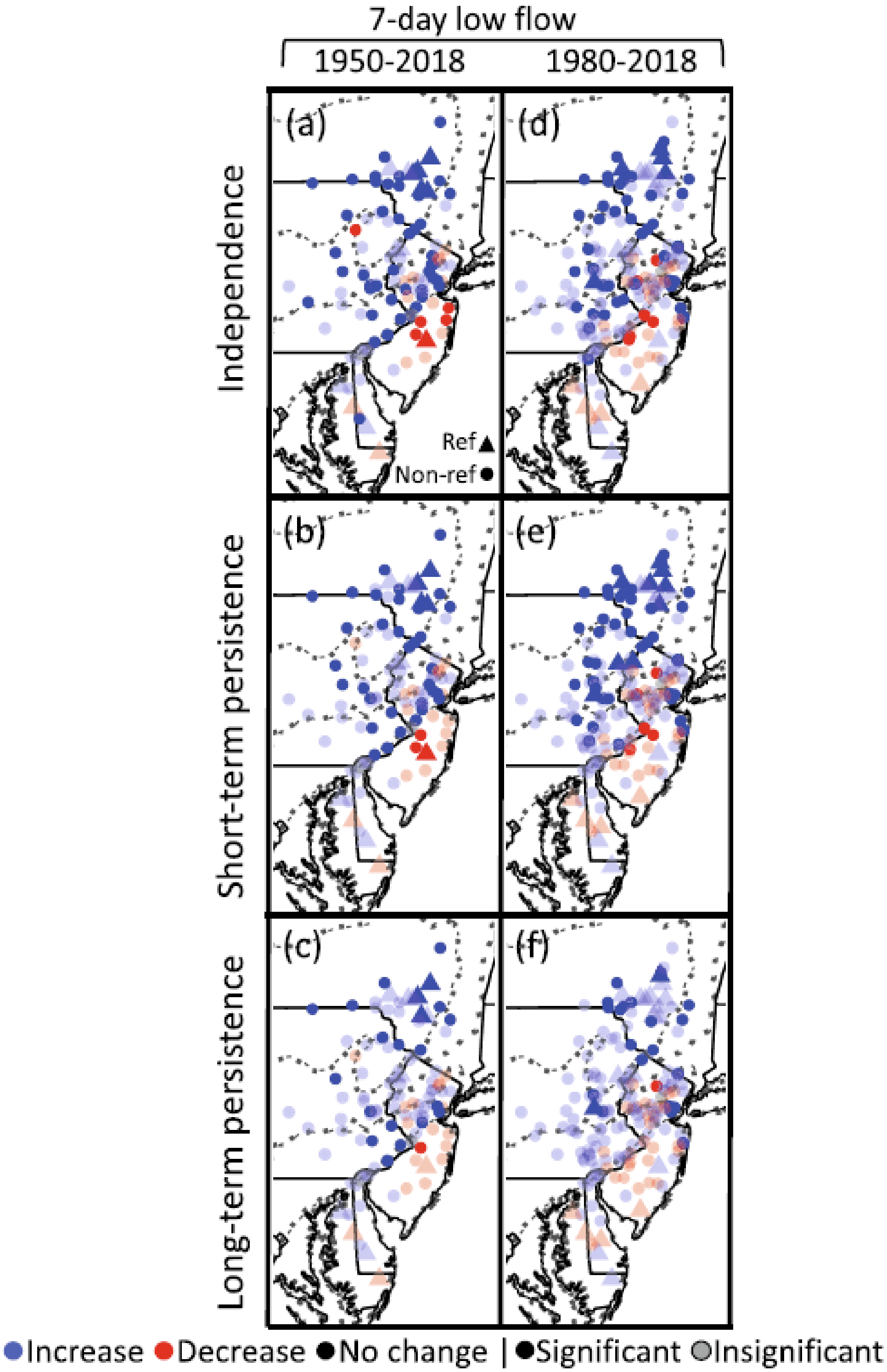


Figure 35: *Adopted from (Hammond & Fleming, 2021). Trends in 7-day low flow 1950–2018 (a–c) and 1980–2018 (d–f). Three methods of trend significance are assessed: Mann-Kendall with assumption of independence (a,d), short-term persistence (b,e), and long-term persistence (c,f). Trends with positive slopes are shown in blue, negative in red, and no change in gray: Transparent symbols have p-values > 0.05. Reference gages are shown by triangles while non-reference gages are shown by circles.*

6. NATURAL RESOURCE ASSESSMENT

6.1. Stream low flow patterns (Hammond and Fleming, 2021)

The annual 7-day low flow is likely to represent baseflow; therefore, changes in the annual 7-day low flow provide insight into how the natural resource may be responding to the drivers affecting it. A recent study published by the USGS evaluates patterns in annual 7-day low flow (among other low flow metrics) at 325 USGS gages in and around the Delaware River Basin for two periods: 1950–2018 and 1980–2018 (Hammond & Fleming, 2021). In addition to presenting temporal and spatial patterns of low flow metrics, the study identifies the drivers of these patterns, including explanatory variables from three categories: (1) climatic, (2) land use and human alteration, and (3) topography, soils, and geology. For more detailed information on the study, it is advisable that the reader refer to the report directly.

Hammond & Fleming, 2021 selected to evaluate watersheds from the USGS GAGES-II database. The term GAGES stands for "Geospatial Attributed of Gages for Evaluating Streamflow (version II)", and the database provides geospatial data and classifications for 9,322 stream gages which have had either 20+ years of discharge record since 1950, or were active as of water year 2009 (Falcone, 2011). Geospatial data includes environmental features (e.g., historical precipitation, geology, soils, topography) and anthropogenic influences (e.g., land use, road density, presence of dams, canals, or power plants). A subset of the GAGES-II (2,057 sites) is classified as "reference" meaning they are likely reflective of near-natural flow. A smaller subset of GAGES-II (743 sites) are also noted as part of the USGS Hydro-Climatic Data Network (HCDN) (Slack & Landwehr, 1992), based on updated screening during database development (Falcone, 2011).

Hammond & Fleming, 2021 note that 325 total sites were included in their study, of which 50 are classified as reference gages and a smaller subset (20/50) as HCDN-2009. For all gages in the study, non-parametric Spearman Rank correlations were calculated between each low flow metric and each explanatory variable. To assess how low flow metrics have been changing over time, Hammond & Fleming, 2021 used:

i. Three variations of the non-parametric Mann-Kendall trend test to indicate whether the low flow metric at a site has a positive, negative, or no slope with respect to time (Mann, 1945; {Kendall} R package, McLeod, 2022). The variations apply different assumptions associated with (1) independence (base Mann-Kendall trend test), (2) short term persistence, and (3) long term persistence.
ii. A Theil-Sen estimator to fit linear regressions to each site's low flow metrics to obtain the slope of the trend (reflective of magnitude) (Sen, 1968; Theil, 1950; {zyp} R package Bronaugh & Werner, 2019).

Results of the Mann-Kendall test for the annual 7-day low flow are presented in Figure 35, adopted from Hammond & Fleming, 2021. Blue colors indicate that the 7-day low flow is increasing, whereas red colors indicate that it is decreasing (getting worse). (Hammond & Fleming, 2021) evaluated the significance of these trends and use transparent symbols in Figure 35 where lag-1 autocorrelation returns a *p*-value > 0.05 (meaning that annual datapoints may not be entirely independent of each other). Regardless, Hammond & Fleming, 2021 note that there are regional patterns such as increased low flows over time in the north, and decreased low flows over time in the south (the Coastal Plain).

Hammond & Fleming, 2021 evaluated potential drivers of these low flow trends, including human activity (withdrawals), land use (impervious surface and cultivated land), climate (precipitation, temperature), and geology (permeability, slope, and depth to bedrock). According to their random forest analysis and Spearman rank correlation analysis, withdrawals, impervious area, precipitation, temperature, and slope were among the strongest explanatory variables for trends in low flow metrics. Similarly, McCabe & Wolock, 2020 found that precipitation drives much of the variability in low flow severity for the Delaware River Basin. Ultimately, Hammond & Fleming, 2021 applied a classification and regression tree (CART) analysis to show that sites where (1) precipitation increased significantly, (2) water use decreased, and (3) dam storage increased were more likely to have increased 7-day low flows over time.

It is promising that Hammond & Fleming, 2021 found that low flows have been increasing in much of the Basin (Figure 35), as this finding supports the conclusion that groundwater use has been sustainable—otherwise, low flows would have been expected to decrease along with declining groundwater levels. Similarly, Section 5.1 shows that projected net groundwater withdrawals from the 121 subbasins (where the Sloto & Buxton, 2006 methodology is applicable) did not exceed calculated RI-25 or RI-50 baseflow thresholds in 2020, also suggesting that groundwater use is sustainable. While Hammond & Fleming, 2021 showed some decreasing low flow volumes in the Coastal Plain, this study does not assess a large portion of that area due to complexities associated with the confined aquifer system (discussed in Section 5.1.4).

Hammond & Fleming, 2021 noted that detailed groundwater trend work was not available in their region of study, that five-year estimates of water use were used as an approximation of all water use activity, and that specific knowledge on how water use and/or groundwater levels throughout the Delaware River Basin have changed with time would enhance the interpretation of study results. Incorporating historical groundwater withdrawal results from Thompson & Pindar, 2021 in this study helps to address this recommendation. There also remains the possibility for ensuing work incorporating the groundwater withdrawal projections from Thompson & Pindar, 2021 to a study similar to Hammond & Fleming, 2021, regarding projections of low flows in the Delaware River Basin.

6.2. Groundwater levels

Groundwater levels throughout the Delaware River Basin are monitored primarily by routine measurements and/or data transducers installed at established wells within monitoring networks. Two primary sources of data are shown in Figure 36: (1) The U.S. Geological Survey National Water Information System (USGS NWIS) (USGS, 2022), and (2) the Delaware Geological Survey Groundwater Monitoring Network (DGS, 2022). Only wells within the Delaware River Basin boundary and with data reported after 2019 are included (990 sites). Each site was categorized by the initial year of measurement (darker colors are older) and the number of measurements (bigger symbols are more frequently measured).

It is immediately evident from Figure 36 that there is more focus on monitoring groundwater levels in the Coastal Plain of the Delaware River Basin than elsewhere, simply based on the distribution of well density. It should be noted that well depth and/or target aquifer is not indicated on Figure 36, and it is likely that many of the wells in the Coastal Plain are monitoring piezometric levels associated with confined aquifers. The wells presented in Figure 36 only consider one parameter (groundwater levels), and do not consider other parameters such as salinity, which is likely another driver for monitoring in the Coastal Plain. Finally, land use patterns also play a role in a need for monitoring groundwater levels (such as agriculture in Delaware and Southern New Jersey which are known to rely on irrigation) and may help explain the higher density of monitoring wells in the Coastal Plain.

This section provides a preliminary analysis of trends in groundwater levels for a subset of wells initially presented in Figure 36; specifically, those which are not in the Coastal Plain (to avoid complexities associated with the confined aquifer network) and have at least ten years with data. This reduced the total number of sites from 990 to 169. The analysis is based largely on the methods presented in Hammond & Fleming, 2021 for assessing low flow patterns in streams, but is not as thorough in breadth, nor in the analysis of drivers behind observed trends. Steps taken to analyze groundwater level data include:

1. **Download the data.** Using the USGS developed R package {dataRetrieval} (De Cicco et al., 2022) to obtain data at each of the 169 sites, including two data types: (1) “daily value” (*dv-data*) for sites which have real-time data recorded by scientific instruments, paired with statistical parameter 00003 (daily mean), and (2) “groundwater level measurements” (*gw-data*) which are manual measurements. Site locations were geo-processed in relation to existing GIS shapefiles using the R package {sf} (Pebesma, 2018).

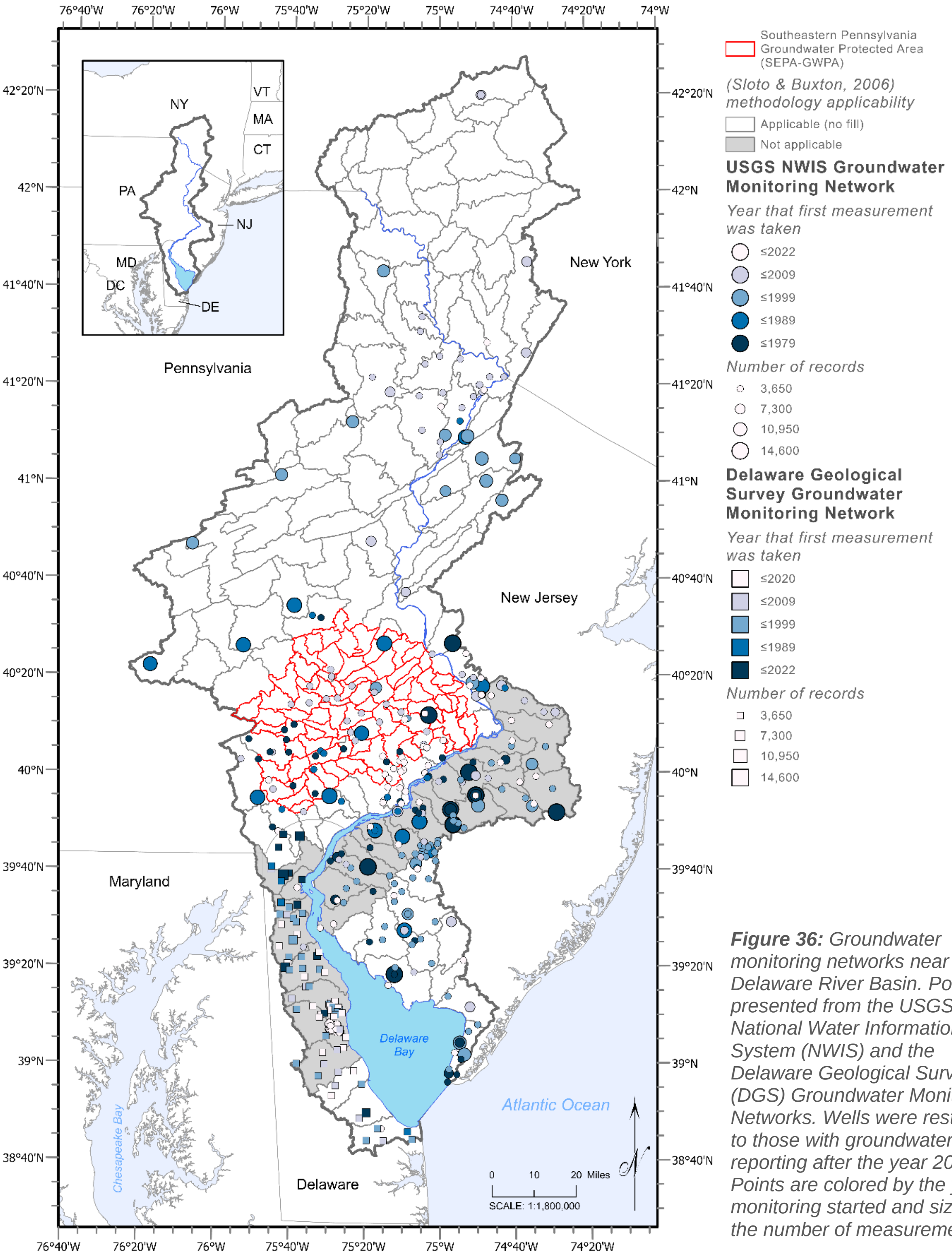


Figure 36: *Groundwater monitoring networks near the Delaware River Basin. Points are presented from the USGS National Water Information System (NWIS) and the Delaware Geological Survey (DGS) Groundwater Monitoring Networks. Wells were restricted to those with groundwater levels reporting after the year 2019. Points are colored by the year monitoring started and sized by the number of measurements.*

2. **Calculate representative annual groundwater "low-level" statistics.** For dv-data, an annual groundwater low-level statistic was computed to be the value at which exceeded 98% of the daily mean depth to water measurements. For gw-data, the annual groundwater low-level statistic was taken as the maximum depth to water measurement for the calendar year. Preference in a given calendar year was given to the dv-data low-level statistic; however, if dv-data were not present, the gw-data low-level statistic was included in the dataset (if present). Sites with fewer than ten years of low-level statistic values were excluded from the analysis.
3. **Perform trend analyses**. First, a single variation of the non-parametric Mann-Kendall trend test was applied to each time-series (as opposed to the other two variations used in Hammond & Fleming, 2021, which consider short-term and long-term persistence) using the R package {Kendall} (McLeod, 2022). Results of the test were primarily used to determine whether the presence of an increasing or decreasing trend could be considered significant (p value < 0.05). A Theil-Sen algorithm was then applied to assess the relative trend magnitude based on the slope of the linear regression, using the R package {zyp} (Bronaugh & Werner, 2019).

The results of the trend analysis are shown in Figure 37 for the 169 sites which met the analysis criteria. Sites with decreasing depth to water measurements indicate rising groundwater tables and are color-coded blue. The opposite trends of a lowering water table (increasing measurement values) are color-coded red, while neutral trends are white. The difference in point shape distinguishes whether the Mann-Kendall p-value at was above or below the threshold of 0.05.

Based on this limited analysis, trends are consistent with the stream low flow trend findings presented in Hammond & Fleming, 2021, and appear logical in comparison to the groundwater availability analysis presented in this report. There were 76 sites with a trend of decreasing depth to water measurements indicating that the groundwater elevation is rising (34 of these sites had a statistically significant trend). There were only 16 sites where the trend in depth to water measurements was increasing, indicating that the groundwater elevation is dropping (4 of these sites had a statistically significant trend). There were 77 sites with "neutral" trends, meaning the Theil-Sen slope was between -0.05 and 0.05 feet per year.

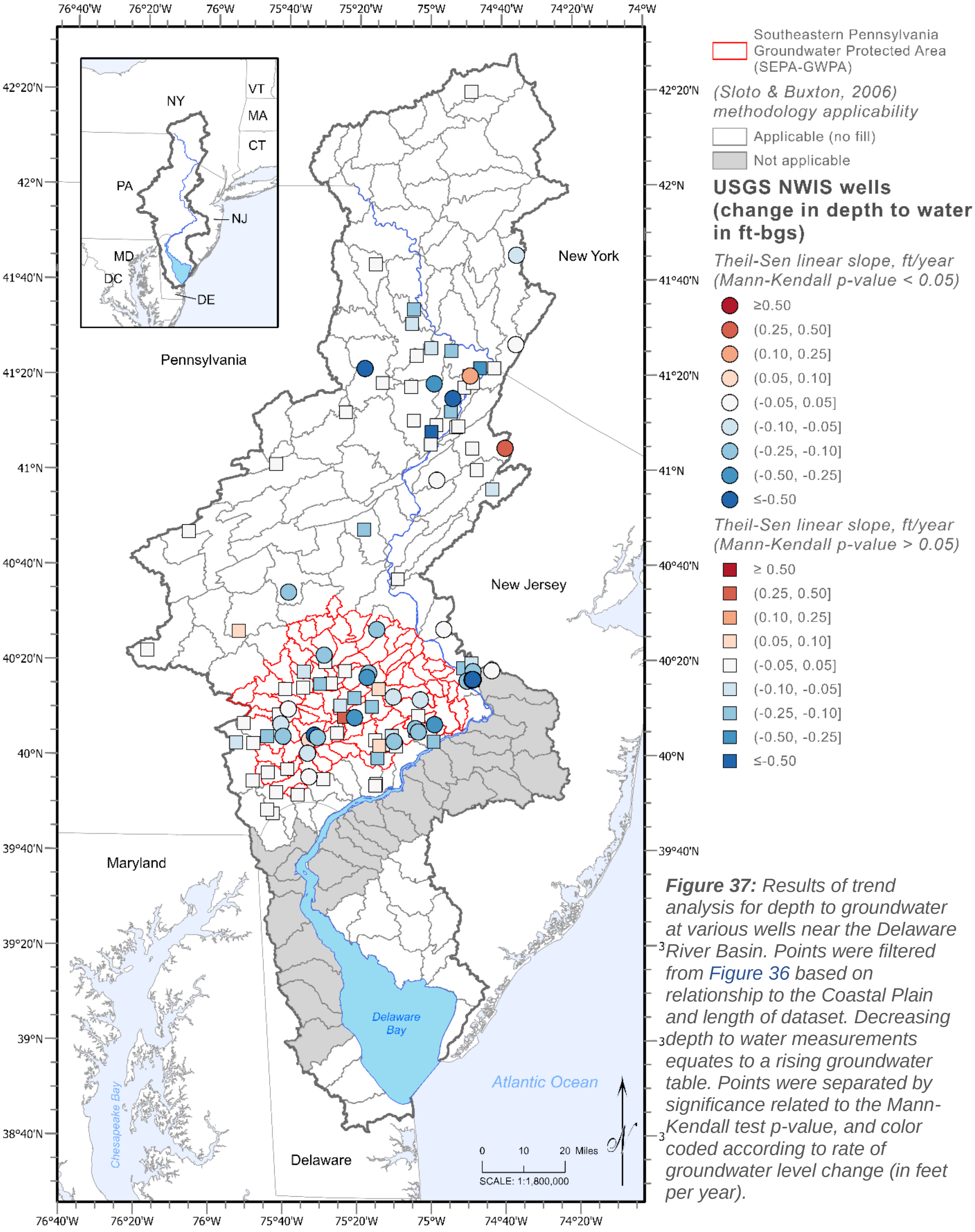


Figure 37: *Results of trend analysis for depth to groundwater at various wells near the Delaware River Basin. Points were filtered from Figure 36 based on relationship to the Coastal Plain and length of dataset. Decreasing depth to water measurements equates to a rising groundwater table. Points were separated by significance related to the Mann-Kendall test p-value, and color coded according to rate of groundwater level change (in feet per year).*

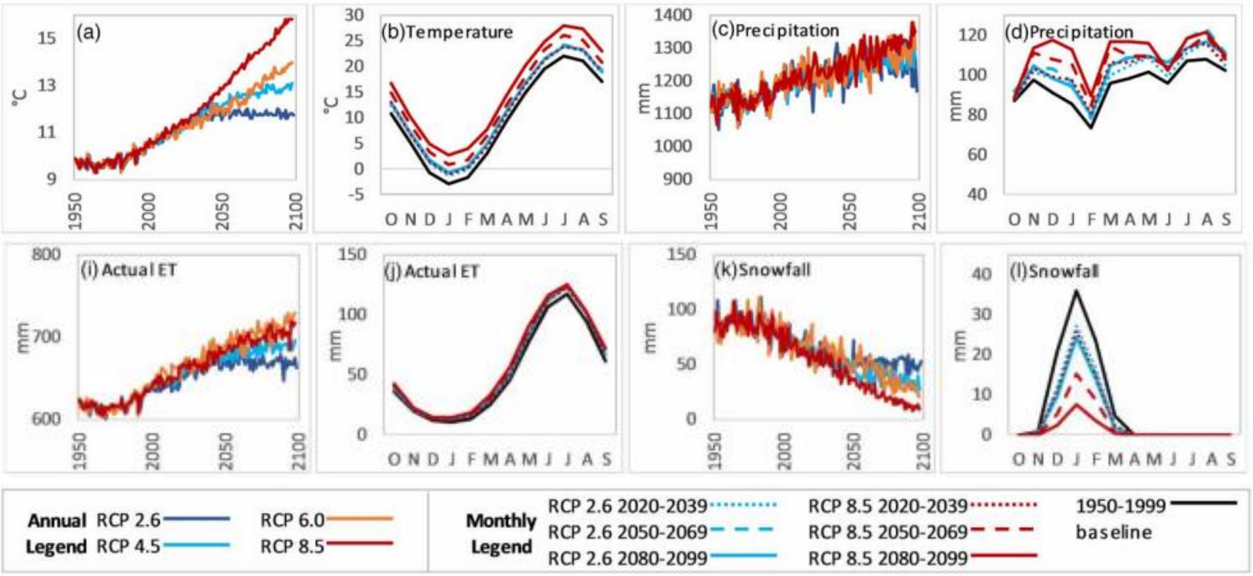


***Figure 38**: Delaware River Basin hydrological model data based on future climate projections adopted from Hawkins & Woltemade, 2021. Time series of projected mean annual temperature (A), precipitation (C), actual evapotranspiration (I), and snowfall (K) are shown as are monthly average temperature (B), precipitation (D), actual evapotranspiration (F), and snowfall (H) across each scenario. Colors represent various emissions scenarios, with black representing the historical baseline scenario, RCP 2.6 (dark blue in A,C,E,G and light blue in B,D,F,H) representing the lowest-emission scenario and RCP 8.5 (dark red) representing the highest-emission scenario.*

7. CLIMATE CHANGE & GROUNDWATER

In this study, climate change impacts were not addressed in the screening tool analyses. However, it is known that Basin-wide precipitation and temperature patterns are changing. Hawkins & Woltemade, 2021Hawkins & Woltemade, 2021 note that compared to a 1950–1999 baseline, annual average temperature in the Basin is expected to increase by 2 to 5.5˚C depending on the emissions scenario by 2080–2099. In locations inland, where there are fewer moderating effects from the Atlantic Ocean, greater warming is expected to occur. Warming is expected to be relatively consistent throughout the year, except slightly lower during spring (Figure 38). It is also expected that across the Basin, precipitation and actual evapotranspiration (ET) will increase, while winter snowpack will decrease (Hawkins & Woltemade, 2021; Williamson et al., 2016). Like temperature, changes in precipitation are expected to vary across the Basin. In particular, the Upper Basin, which has historically had significant snowfall, will likely have more rainfall and less snow water storage. The Lower Basin is expected to see a greater increase in summer precipitation than the Upper Basin (Figure 38).

These changes in climatic conditions are expected to impact processes that are important for groundwater resource availability, including groundwater recharge and surface water–groundwater interactions. Specific, quantitative groundwater predictions are difficult to make due to the uncertainty behind temperature and precipitation increases, and because it is difficult to know precisely how these climate trends will impact groundwater (NJDEP, 2020). However, some consensus has begun to emerge in literature.

Groundwater aquifers are typically recharged by effective precipitation and/or interactions with surface water bodies, such as rivers and lakes. Water can reach an aquifer quickly through large pores and fissures, or slowly by infiltrating through soil and permeable rocks. (Kumar, 2012). Milder winters and earlier snowmelt may lead to increased wintertime recharge but reduced spring recharge (Amanambu et al., 2020). In the summer, increased evapotranspiration may cause greater, longer soil deficits and reduced recharge. But uncertainty remains about how climate change will affect seasonal recharge and groundwater availability (Dong et al., 2019).

Groundwater supply may be impacted due to an extended growing season; warmer temperatures for prolonged periods each year make it possible for crops to grow longer. A greater need for irrigation will put additional stress on water supplies and occur in conjunction with peaks in water demand during the summer months (Kumar, 2012; NJDEP, 2020). A decrease in groundwater supply may lead to land subsidence due to the compaction of soil that formerly held water (Amanambu et al., 2020; Dong et al., 2019).

Declining groundwater supply in the Coastal Plain may also lead to saltwater intrusion. Saltwater intrusion occurs when saltwater moves into aquifers that formerly contained freshwater; drought, increased groundwater withdrawal, and sea-level rise can all contribute to saltwater intrusion. The Coastal Plain has seen an increase in reported groundwater withdrawals for irrigation, and pumping may further increase as the growing season extends due to climate change (Thompson & Pindar, 2021). The presence of freshwater in coastal aquifers currently limits saltwater intrusion, but as pumping increases and freshwater levels decrease, saltwater intrusion could more readily occur. Rising sea levels may also contribute to saltwater intrusion of freshwater aquifers (Amanambu et al., 2020). Furthermore, work done by USGS has suggested sea-level rise will increase groundwater flow to freshwater wetlands and saltwater intrusion into coastal aquifers (Fiore et al., 2017). Increased flow from coastal aquifers may impact groundwater supply in the Coastal Plain. While there is a possibility of impacts to groundwater due to climate change, the extent of these impacts is currently uncertain.

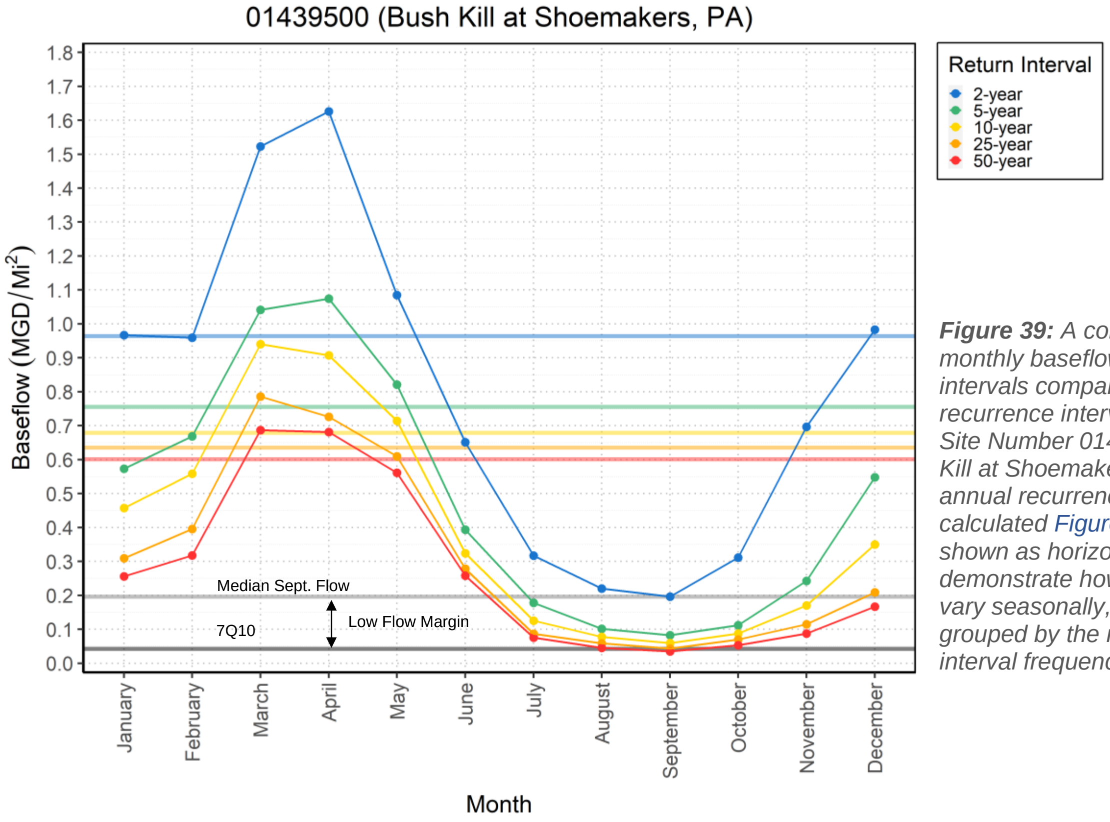


Figure 39: *A comparison of monthly baseflow recurrence intervals compared to annual recurrence intervals for USGS Site Number 01439500 (Bush Kill at Shoemakers, PA). The annual recurrence intervals calculated Figure 4B are shown as horizontal lines. To demonstrate how baseflows vary seasonally, data are grouped by the recurrence interval frequency.*

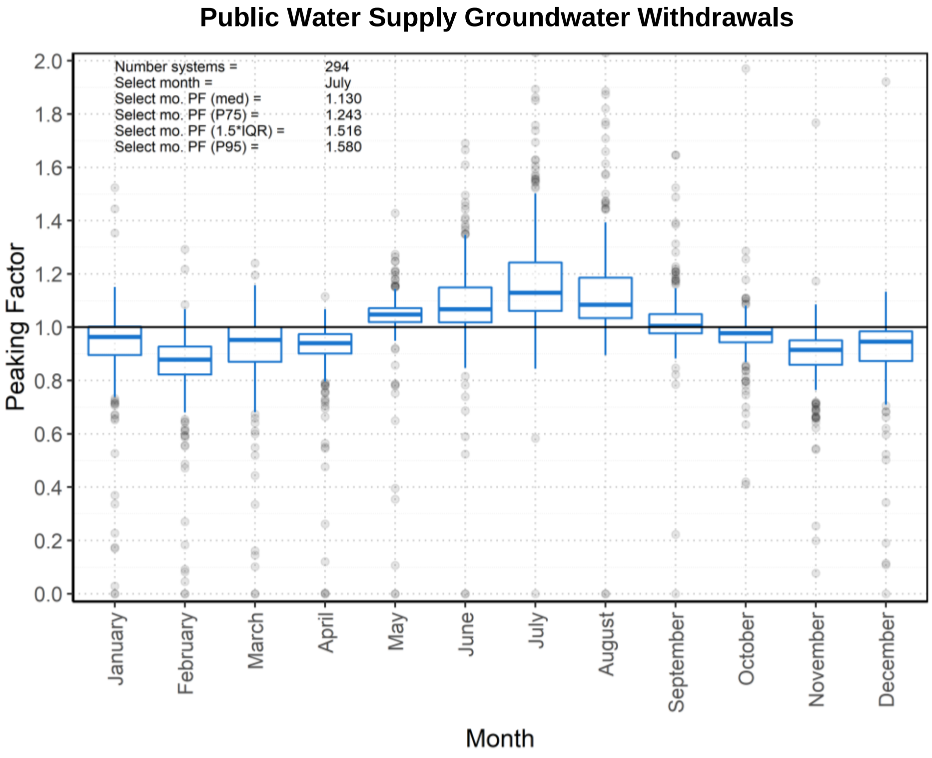


Figure 40: *Monthly peaking factors for public water supply systems in the Delaware River Basin. This data considers 294 systems that withdrawal groundwater, based on data used in developing the projections provided in Thompson & Pindar, 2021.*

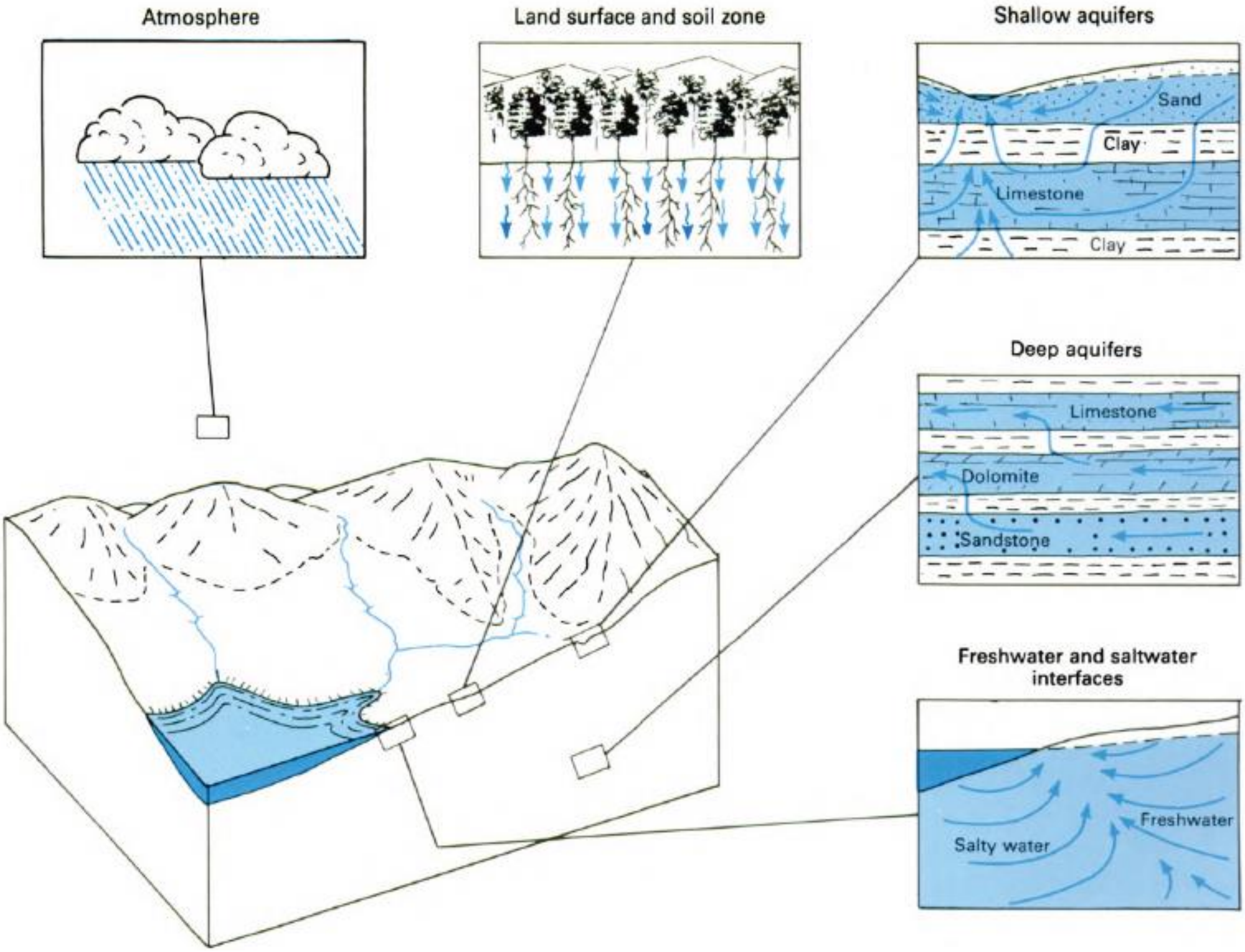
8. SEASONALITY

This study focused on "annual average baseflow" values and has therefore assessed groundwater availability on an annual basis. However, it is well known that there are sub-annual trends in both the natural resource availability and the withdrawal/demand for groundwater resources. Revisiting the example USGS Site Number 01439500 (Bush Kill at Shoemakers, PA) from Section 2.1, the same hydrograph-separated data can be averaged over a monthly timeframe instead of an annual timeframe. For each year of data, this analysis results in 12 monthly baseflow recurrence interval curves. In order to better observe how baseflows typically change throughout a given type of year (e.g., RI-2 being a normal year, or RI-50 being a very dry year), it is convenient to group the common monthly recurrence intervals as shown in Figure 39 rather than showing 12 monthly recurrence interval curves. Additionally, the annual average baseflow recurrence interval values from Figure 4B have been added as horizontal lines for visual comparison. From this analysis, it is clear that there can be great discrepancies in the RI-baseflow calculated using annual average data compared to the RI-baseflow for a typical low flow month (September). Note that annual recurrence interval baseflow values do not represent the average of monthly values because all months in a year may not be of the same distribution (e.g., RI-25).

Compounding the issue of variable groundwater monthly baseflows is the variable withdrawal demand. An example is shown in Figure 40, which assesses the monthly data used in the analysis performed by DRBC to project annual withdrawal volumes (Thompson & Pindar, 2021). That analysis considered 294 public water supply systems that withdraw groundwater in the Basin and assessed how the average monthly groundwater withdrawal volumes compared to the average annual groundwater withdrawal volume.

The median monthly peaking factors were taken for each system, and the distribution of groundwater peaking factors are presented by month. From this assessment, DRBC found that groundwater is not withdrawn at a constant rate throughout the year, and that there are relatively more withdrawals in the summer and fewer in the winter. The peak month for public water suppliers withdrawing groundwater is July, with the median rate of the 294 systems reviewed approximately 13% higher than the annual average.

Notably, some methods of assessing groundwater availability capture seasonal components. The Stream Low Flow Margin Method (Domber et al., 2013) used by NJDEP quantifies the available resources by defining the low flow margin as the difference between a stream's 7Q10 (a typical drought flow) and the September median flow (a typical dry-season flow). In the example shown in Figure 39, the 7Q10 was calculated using the USGS Surface Water Toolbox version 1.0.5 (Kiang et al., 2018), and the median September flow was equivalent to the 50th percentile flow (i.e., the RI-2 baseflow). Graphing these values, it is clear to visualize the difference between what might be considered available natural resources using the Stream Low Flow Margin Method, versus the method used in this study which might consider the RI-25 or RI-50 annual average baseflow. Applying the same annual average withdrawal rate to the two methods (MGD/mi^2) will yield significantly different results. The Stream Low Flow Margin Method has a more conservative threshold to screen areas for further evaluation. Correcting the annual average withdrawal rate by a peaking factor for the same month (September) will again yield more conservative results. Alternatively, an assessment could be completed by defining the low flow margin using the July RI-2 baseflow and comparing the results against withdrawals corrected by the July peaking factor (highest month of withdrawals). Regardless of the exact approach, this example assessment on seasonality effects demonstrates that improvement upon the annual average approach currently used by DRBC is both justified and feasible.



Adopted from the U.S. Geological Survey Water-Supply Paper 2220, *Basic Ground-Water Hydrology*. (Heath, 1983)

9. CONCLUSIONS

9.1. Summary

This study provides a review of groundwater assessment methodologies used in and around the Delaware River Basin. While numerous methods have and are being applied, the Delaware River Basin Commission has routinely used the Basin-wide methodology developed by Sloto & Buxton, 2006 which compares net groundwater withdrawals against annual baseflows developed for each of 147 subbasins at 25-year and 50-year recurrence intervals (Figure 2). A similar methodology has historically been used to assess groundwater availability in the Southeastern Pennsylvania Groundwater Protected Area (SEPA-GWPA): comparing net withdrawals against regulatory groundwater withdrawal limits (18 C.F.R. Part 430, 1980), which are equivalent to the RI-25 baseflow in each of 76 subbasins (Figure 6) (USGS, 1998). A primary difference between this study and previous DRBC studies on groundwater availability is the evaluation of Sloto & Buxton, 2006 methodology applicability within the Coastal Plain (Section 5.1.4). From assessments of well depth and unconfined aquifer thickness, there are eight subbasins in Delaware and eighteen subbasins in New Jersey where the Sloto & Buxton, 2006 methodology is not applied, as withdrawals primarily come from confined aquifers (Figure 26). Other studies on groundwater availability in the Coastal Plain were referenced (Section 5.1.4.3) and projected withdrawals from these subbasins were discussed (Section 5.1.4.4).

Historical and projected water withdrawal data were adopted from Thompson & Pindar, 2021, who showed that on average, historical withdrawals from the Delaware River Basin have been about 5.4% groundwater and 94.6% surface water. In 2017, withdrawals were 6.3% and 93.7%, respectively, which equates to approximately 433 MGD of groundwater and 6,476 MGD of surface water. The groundwater withdrawal data were adjusted to represent “net” withdrawals from each planning subbasin (Section 3.3.1).

- The model for projected Basin net groundwater withdrawals estimates approximately 356 MGD in 2018 and 358 MGD in 2060, suggesting a constant or equilibrium type projection (Figure 16A). However, analysis of the 147 subbasins show that 37 are projected to increase withdrawals (totaling +23.5 MGD), 78 are projected to have neutral conditions ($-0.10 < \Delta < 0.10$ MGD), and 32 subbasins are projected to decrease withdrawals (totaling -21.5 MGD) (Figure 17).
- The model for projected SEPA-GWPA net groundwater withdrawals estimates approximately 45 MGD in 2018 and 43 MGD in 2060, suggesting a constant or equilibrium type projection (Figure 16B). However, analysis of the 76 subbasins show that 12 are projected to increase withdrawals (totaling +3.5 MGD), 55 are projected to have neutral conditions ($-0.10 < \Delta < 0.10$ MGD), and 7 subbasins are projected to decrease withdrawals (totaling -5.3 MGD). Note that two subbasins did not have reported withdrawals (SP-32 and SP-68), as indicated in Table 4.

Given the projected net groundwater withdrawal for each subbasin (at Basin-wide scale and the SEPA-GWPA scale) as well as an upper 95th percentile predictive limit, a comparison is feasible against respective recurrence interval baseflows:

- At the Basin-wide scale, analyses for the RI-25 baseflow scenario (2020 projected, 2060 projected, 2060 95%PI) presented in Figure 19 and the RI-50 baseflow scenario (2020 projected, 2060 projected, 2060 95%PI) presented in Figure 20**:**, all of which are summarized in Table 3. Subbasin DB-067 (Little Lehigh Creek, PA) is the subbasin projected to use the highest percent of available groundwater: approximately 60% for RI-50 baseflow and approximately 50% for RI-25 baseflow. Considering the 95th percentile predictive interval, DB-067 is the only subbasin to extend beyond the 75% threshold and highlights the importance of accounting for uncertainty in these projections. While most subbasins do not show a significant increase in groundwater withdrawals as a percent of available baseflow from 2020 to 2060, those that do (DB-145, DB-054, DB-147, DB-133, and

DB-067) may be more vulnerable to a severe drought in the 2050s than they would be to a severe drought in the 2020s.

- At the SEPA-GWPA scale, analyses for the RI-25 baseflow scenario (2020 projected, 2060 projected, 2060 95%PI) presented in Figure 27, and analyses for the RI-50 baseflow scenario (2020 projected, 2060 projected, 2060 95%PI) presented in Figure 28, all of which are summarized in Table 4. There are two subbasins which show existing or projected net groundwater withdrawals above the RI-25 and RI-50 baseflows: SP-03 (Pine Run in the Neshaminy Creek headwaters) and SP-29 (Crow Creek in the Schuylkill River watershed). More detailed assessments considering additional factors such as well depth and local geology were performed for SP-03 (Section 5.2.3.1) and SP-29 (Section 5.2.3.2), both of which did not reveal localized issues. Given the smaller size of the SEPA-GWPA subbasins than the 147 subbasins, it provides the opportunity to screen areas with higher densities of withdrawals at a finer resolution—therefore, there are many more subbasins reaching percentage thresholds (e.g., 50%, 75%, 100%). Like the Basin-wide analysis, the incorporation of uncertainty in the form of prediction intervals provides useful information for understanding possible outcomes.

The results from these screening tools indicate that groundwater is being used at sustainable rates in most areas within the Delaware River Basin (not assessing confined aquifers in the Coastal Plain). Therefore, Section 6 attempts to draw parallels between these groundwater availability findings and possible responses observed within the natural environment (i.e., stream low flow trends and groundwater elevation trends). A recent study published by the USGS (Hammond & Fleming, 2021) evaluates patterns in several low flow metrics at 325 USGS gages in and around the Delaware River Basin for two periods: 1950–2018 and 1980–2018. Hammond & Fleming, 2021 show that annual average 7-day low flow volumes have statistically significant increasing trends in much of the Delaware River Basin, while some low flows in the Coastal Plain have statistically significant decreasing trends (Figure 35); they spend a great deal of effort assessing the natural and human drivers behind the low flow increases. Results from Hammond & Fleming, 2021 are promising from a groundwater availability perspective: an observed increase in low flows support the conclusion that groundwater use has been sustainable—otherwise, low flows would have been expected to decrease along with declining groundwater levels. Hammond & Fleming, 2021 also noted that detailed groundwater trend work was not available and would be valuable. To this end, this study assessed available groundwater level data in Section 6.2, using similar statistical trend methods as Hammond & Fleming, 2021. Based on this limited analysis (Figure 37), annual low groundwater levels showed evidence of rising across much of the Basin (outside the Coastal Plain) are consistent with observed increasing stream low flow trends.

The effects of climate change were only minimally included in this study via incorporation into projections of water withdrawals for irrigation purposes (Thompson & Pindar, 2021); however, many of the primary regions for irrigation were excluded from the screening tool as they are located in the Coastal Plain. Therefore, Section 7 provides qualitative insights based on review of pertinent literature on climate change as it related to groundwater systems within the Delaware River Basin. The discussion covers projected Basin temperature increases, expected patterns and timing of future precipitation and evapotranspiration, the possibility for an extended growing season, and saltwater intrusion.

Finally, this study assessed the possibility of assessing natural resource availability in terms of seasonal recurrence intervals, or a metric which includes a seasonal component (such as the Low Flow Margin Method used by NJDEP). It is known that the late summer is a time of decreased baseflow (Figure 39) and increased demand on the natural resources (Figure 40). Therefore, future investigations into groundwater availability may be well advised to consider seasonal effects as a part of the scope of study.

9.2. Recommendations

Often, when conducting studies, researchers must consider external constraints such as time, funding, and the intended application of the results. Consequently, there is room for improvement in most studies. This research is no different, and it is intended that the methods used in this study are developed with the future in mind for continued improvement.

Some specific recommendations may help guide future groundwater availability assessments using baseflow recurrence intervals. The recurrence interval baseflows used for the 147 subbasins in the Delaware River Basin were calculated in Sloto & Buxton, 2006 at various USGS gaging “index stations” using data through 2001 (23 sites for fractured rock areas), and data through 2004 (25 sites for the Coastal Plain area). Annual average recurrence intervals from these index stations were apportioned to ungaged subbasins via a geologic index approach (fracture rock area) and a combination land-use/geologic index approach (Coastal Plain). Based on the review and findings presented in this DRBC study, recommendations include:

a. Re-assessment of the index stations used in Sloto & Buxton, 2006 (using the same methods) could take advantage of the 20 additional years of available streamflow data to update recurrence interval baseflow values and possibly assess temporal trends in the data.

b. Use of theoretical probability distributions fit to baseflow data would likely provide a beneficial opportunity for comparison against empirical probabilities (e.g., Figure 4).

c. Assessment of seasonal patterns in both recurrence intervals and withdrawals will provide better resolution for resource planning.

d. Use of an ensemble of baseflow separation algorithms for hydrograph analysis would provide a more robust approach than Sloto & Buxton, 2006, which used the HYSEP Local Minimum method only (Sloto & Crouse, 1996). For example, the USGS GW Toolbox currently offers six different algorithms (Barlow et al., 2015). This approach may also offer the potential to calculate confidence intervals around recurrence interval curves to help further quantify the uncertainty in such groundwater availability analyses.

e. Use of an alternative to a geologic index approach may provide a better understanding of the accuracy of recurrence interval baseflow estimates in ungaged streams. For example, statistical correlation parameters related to methods such as multi-variate regression techniques were used to estimate baseflows for Pennsylvania streams in Stuckey, 2006.

f. Incorporation of additional groundwater source metadata similar to the NJDEP “reported formation” to help disseminate where groundwater may actually be withdrawn from (as was assessed in Section 5.1.4.2) may be helpful as a standard practice in groundwater availability assessments.

g. While numerous aspects of climate change have been widely studied, it appears that there has only been a small focus on the climate change impacts to groundwater (as were discussed in Section 7). This topic is likely an area for broad future research and application to the Delaware River Basin.

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10. REFERENCES

18 C.F.R. Part 410. (2013). *Delaware River Basin Water Code*. With amendments through December 4, 2013. Delaware River Basin Commission. https://www.nj.gov/drbc/library/documents/watercode.pdf

18 C.F.R. Part 430. (1980). *Ground Water Protection Area: Pennsylvania*. Revised to Include Amendments through June 23, 1999. Delaware River Basin Commission. https://www.nj.gov/drbc/library/documents/gwpa_regs.pdf

27 Pa. Cons. Stat. § 3101, et seq. *Chapter 31 - WATER RESOURCES PLANNING.*

Amanambu, A. C., Obarein, O. A., Mossa, J., Li, L., Ayeni, S. S., Balogun, O., Oyebamiji, A., & Ochege, F. U. (2020). Groundwater system and climate change: Present status and future considerations. *Journal of Hydrology*, *589*, 125163. https://doi.org/10.1016/j.jhydrol.2020.125163

Andres, S., McQuiggan, R. W., & He, C. (2019). *Open File Report No. 53, Kent County Groundwater Monitoring Project: Results of Subsurface Exploration*. Newark, Delaware. Delaware Geological Survey. https://www.dgs.udel.edu/publications/ofr53-kent-county-groundwater-monitoring-project-results-subsurface-exploration

Andres, S. A., Coppa, Z. J., He, C., & McKenna, T. E. (2018). *Report of Investigations No. 82, Souther New Castel - Northern Ken Counties Groundwater Monitoring Project: Results of Subsurface Exploration and Hydrogeological Studies*. Newark, Delaware. Delaware Geological Survey. https://www.dgs.udel.edu/sites/default/files/publications/RI82.pdf

Baldwin, H. L., & McGuinness, C. (1963). *A Primer on Ground Water*. Washington, D.C. U.S. Geological Survey. https://pubs.usgs.gov/gip/7000056/report.pdf

Ballaron, P. B., Gavin, A., Pody, R. D., & Ladd, D. S. (2005). *Groundwater Management Plan for the Susquehanna River Basin*. Harrisburg, Pennsylvania. Susquehanna River Basin Commission.

Barlow, P. M., Cunningham, W. L., Zhai, T., & Gray, M. (2015). *U.S. Geological Survey Groundwater Toolbox, A Graphical and Mapping Interface for Analysis of Hydrologic Data (Version 1.0)—User Guide for Estimation of Base Flow, Runoff, and Groundwater Recharge From Streamflow Data*. Techniques and Methods Book 3, Chapter B10. Reston, Virginia. U. S. Geological Survey. https://doi.org/10.3133/tm3B10

Berg, T. M., Edmunds, W. E., Geyer, A. R., & and others. (1980). *Geologic map of Pennsylvania (2nd ed.)*. 4th ser., Map 1, 3 sheets. Pennsylvania Geological Survey. http://maps.dcnr.pa.gov/publications/Default.aspx?id=712

Bronaugh, D., & Werner, A. (2019). *{zyp} zyp: Zhang + Yue-Pilon Trends Package*. R package version 0.10-1.1. Pacific Climate Impacts Consortium. https://CRAN.R-project.org/package=zyp

Byun, S. A., Kwityn, E., Pindar, C., & Thompson, M. (2019). *State of the Basin 2019*. Ewing, New Jersey. Delaware River Basin Commission. https://www.nj.gov/drbc/about/public/SOTB2019.html

Carleton, B. G. (2021). *Simulation of Potential Water Allocation Changes, Cape May County, New Jersey*. Scientific Investigations Report 2020-5052. Reston, Virginia. U.S. Geological Survey. https://doi.org/10.3133/sir20205052

CDM & DRBC. (2005). *Methodology for Statewide Water Demand Forecast with Pilot Stud.* Camp, Dresser, and McKee (CDM) & Delaware River Basin Commission. https://files.dep.state.pa.us/Water/Division%20of%20Planning%20and%20Conservation/StateWaterPlan/StateWaterPlanPrinciples/Appendix_I.pdf

Cohen, S. P. (1997). *Draft Statewide Watershed Management Framework Document for the State of New Jersey*. Trenton, New Jersey. New Jersey Department of Environmental Protection (NJDEP). https://www.nj.gov/dep/watershedrestoration/docs/frame97fixed.pdf

Cushing, E. M., Kantrowitz, I. H., & Taylor, K. R. (1973). *Water resources of the Delmarva Peninsula*. U.S. Geological Survey Professional Paper 882 (Professional Paper). https://doi.org/10.3133/pp822

De Cicco, L. A., Lorenz, D., Hirsch, R. M., Watkins, W., & Johnson, M. (2022). *{dataRetrieval} dataRetrieval: R packages for discovering and retrieving water data available from U.S. federal hydrologic web services*. Version 2.7.11. Reston, Virginia. U.S. Geological Survey. https://doi.org/10.5066/P9X4L3GE

Denver, J. M., & Nardi, M. R. (2016). *Thickness of the Surficial Aquifer, Delmarva Peninsula, Maryland and Delaware*. U.S. Geological Survey data release. U.S. Geological Survey; Maryland-Delaware-D.C. Water Science Center. https://doi.org/10.5066/F7610XFT

dePaul, V. T., Rosman, R., & Lacombe, P. J. (2009). *Water-Level Conditions in Selected Confined Aquifers of the New Jersey and Delaware Coastal Plain, 2003*. Scientific Investigations Report 2008-5145. Reston, Virginia. U.S. Geological Survey. https://doi.org/10.3133/sir20085145

DGS. (1993-2015). *Delaware Geological Survey Geologic Map Series No. 8, 11, 12, 15, 16, 17, 18, 19, 20, 21, 22, and 23*. Newark, Delaware. Delaware Geological Survey, University of Delaware. https://www.dgs.udel.edu/data

DGS. (2005-2007). *Delaware Geological Survey Geologic Map Series No. 13 and 14*. Newark, Delaware. Delaware Geological Survey, University of Delaware. https://www.dgs.udel.edu/data

DGS. (2021). *Delaware Groundwater Monitoring Network* [(website)]. Delaware Geological Survey. https://www.dgs.udel.edu/projects/delaware-groundwater-monitoring-network

DGS. (2022). *Delaware Geological Survey Groundwater Monitoring Network*. accessed April 5, 2022. Delaware Geological Survey. http://data.dgs.udel.edu/sites/groundwater/recent-and-historical-groundwater-level-data.html

DNREC. (1999). *Delaware Comprehensive State Groundwater Protection Program.* Delaware Department of Natural Resources and Environmental Control. https://documents.dnrec.delaware.gov/wr/Water-Supply/CSGWPP.pdf

DNREC. (2021). *Salt in Our Water — Saltwater Intrusion and Inundation in Delaware* [(online article)]. Delaware Department of Natural Resources and Environmental Control. https://dnrec.alpha.delaware.gov/outdoor-delaware/salt-in-our-water/

Domber, S., Snook, I., & Hoffman, J. L. (2013). *Using the Stream Low Flow Margin Method to Assess Water Availability in New Jersey's Water-Table-Aquifer Systems*. Technical Memorandum 13-3. Trenton, New Jersey. New Jersey Department of Environmental Protection (NJDEP). https://www.state.nj.us/dep/njgs/pricelst/tmemo/tm13-3.pdf

Dong, Y., Jiang, Chengsheng, Suri, Mayhah R., Pee, Daphne, Lingkui, Meng, & Rosenberg Goldstein, R. E. (2019). Groundwater level changes with a focus on agricultural areas in the MidAtlantic region of the United States, 2002–2016. *Environmental Research*, *171*(193).

DRBC. (1980). *DRBC Resolution No. 80-18*. Resolution on the Creation of the Southeastern Pennsylania Groundwater Protected Area. Delaware River Basin Commission. https://www.state.nj.us/drbc/library/documents/Res1980-18gwpa.pdf

DRBC. (1981). *The Delaware River Basin: The Final Report and Environmental Impact Statement of the Level B Study*. Ewing, New Jersey. Delaware River Basin Commission.

DRBC. (1998). *Resolution to Amend Ground Water Protected Regulations for Southeastern Pennsylvania with the Establishment of Numerical Withdrawal Limits.* Delaware River Basin Commission.

DRBC. (1999). *RESOLUTION to amend the Ground Water Protected Area Regulations for Southeastern Pennsylvania by the establishment of numerical withdrawal limits for 62 subbasins which are entirely or partially within the Protected Area*. Ewing, New Jersey. Delaware River Basin Commission.

DRBC. (2002). *Resolution Authorizing USGS to Provide Technical Support for The Comprehensive Planning Process.*

DRBC. (2004). *Water Resources Plan for the Delaware River Basin*. Ewing, New Jersey. Delaware River Basin Commission. https://www.nj.gov/drbc/library/documents/BasinPlan_Sept04.pdf

DRBC. (2020). *National Wild and Scenic Rivers in the DRB.* Delaware River Basin Commission. https://www.nj.gov/drbc/basin/wild.html

DRBC. (2021). *Delaware River Basin Commission Water Resources Program FY 2022-2024*. West Trenton, New Jersey. Delaware River Basin Commission. https://www.state.nj.us/drbc/library/documents/WRPFY22-24.pdf

DRBC, & MCPC. (2008). *Upper Wissahickon Creek Special Area Management Plan.* Delaware River Basin Commission; Montgomery County Planning Commission.

DRBC, & PADEP. (1980). *Cooperative Agreement for Management of Ground Water Resources in the Southeastern Pennsylvania Ground Water Protected Area*. Trenton, New Jersey.

Dugan, B. L., Neimeister, M. P., & Andres, S. A. (2008). *Open File Report No. 49, Hydrogeologic Framework of Southern New Castle County*. Newark, Delaware. Delaware Geological Survey.

Eckel, J. A., & Walker, R. L. (1986). *Water Levels in Major Artesian Aquifers of the new Jersey Coastal Plain, 1983*. Water-Resources Investigations Report 86-4028. Trenton, New Jersey. U.S. Geological Survey. https://pubs.usgs.gov/wri/1986/4028/report.pdf

Edwards, R. E., & Pody, R. D. (2005). *Northern Lancaster County Groundwater Study: A Resource Evaluation of the Manheim-Lititz and Ephrata Area Groundwater Basins*. Publication No. 235. Harrisburg, Pennsylvania. Susquehanna River Basin Commission. https://www.srbc.net/our-work/reports-library/technical-reports/235-lancaster-groundwater-study/

Ellis, W., & Price, C. (1995). *Development of a 14-digit hydrologic coding scheme and boundary data set for New Jersey: U.S. Geological Survey water-resources investigations report 95-4134*. 1 sheet, 1:250,000. U.S. Geological Survey. https://www.state.nj.us/dep/gis/digidownload/metadata/statewide/dephuc14.htm

Emmanuel, C. G., & Nicholson, R. S. (2012). *Simulation of Groundwater Flow and Hydrologic Effects of Groundwater Withdrawals from the Kirkwood-Cohansey Aquifer System in the Pinelands of Southern New Jersey*. Scientific Investigations Report 2012–5122. Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/sir/2012/5122/support/sir2012-5122.pdf

Esralew, R. A., & Baker, R. J. (2008). *Determination of Baseline Periods of Record for Selected Streamflow-Gaging Stations in New Jersey for Determining Ecologically Relevant Hydrologic Indices (ERHI)*. Scientific Investigations Report 2008-5077. Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/sir/2008/5077/pdf/sir2008-5077.pdf

ESRI. (2020). *ArcGIS Pro 2.5.0*. Redlands, California. Environmental Systems Research Institute Inc.

N.J.S.A. 13:18A-1 et. seq. (1979). *Pinelands Protection Act*. Trenton, New Jersey. State of New Jersey. https://www.nj.gov/pinelands/cmp/CMP.pdf

Falcone, J. A. (2011). *GAGES-II: Geospatial Attributes of Gages for Evaluating Streamflow*. (Digit. Spat. Data set). U. S. Geological Survey. https://doi.org/10.3133/70046617

Fenneman, N. M., & Johnson, D. W. (1946). *Physiographic divisions of the conterminous U. S.* 1:7,000,000-scale map (GIS Shapefile). Reston, Virginia. U.S. Geological Survey. https://water.usgs.gov/GIS/metadata/usgswrd/XML/physio.xml

Fiore, A. R., Voronin, Lois M., & Wieben, C. M. (2017). *Hydrogeology of, Simulation of Groundwater Flow in,and Potential Effects of Sea-Level Rise on the Kirkwood-Cohansey Aquifer System in the Vicinity of Edwin B. Forsythe V*. Reston, Virginia.

Fischer, J. M., Riva-Murray, K., Hickman,, R. E., Chichester,, D. C., Brightbill,, R. A., Romanok, K. M., & Bilger, M. D. (2004). *Water Quality in the Delaware River Basin, Pennsylvania, New Jersey, New York, and Delaware, 1998–2001*. Circular 1227. Reston, Virginia. U.S. Geological Survey. https://doi.org/10.3133/cir1227

Gary, M., McAfee, R., Jr., & Wolf, C. L. (1972). *Glossary of Geology.*

Gerhart, J. M., & Lazorchick, G. J. (1984). *Evaluation of the Ground-Water Resources of Parts of Lancaster and Berks Counties, Pennsylvania*. U.S. Geological Survey Water-Resources Investigations Report 84-4327. Denver, Colorado. U.S. Geological Survey. https://pubs.usgs.gov/wri/1984/4327/report.pdf

Gillespie, B. D., & Schopp, R. D [R. D.]. (1982). *Low-flow characteristics and flow duration of New Jersey streams*. Open-File Report 81-1110. Trenton, New Jersey. U.S. Geological Survey. https://doi.org/10.3133/ofr811110

Hammond, J. C., Doheny, E. J., Dillow, J. J., Nardi, M. R., Steeves, P. A., & Warner, D. L. (2022). *Scientific Investigations Report* (Scientific Investigations Report). US Geological Survey.

Hammond, J. C., & Fleming, B. J. (2021). Evaluating low flow patterns, drivers and trends in the Delaware River Basin. *Journal of Hydrology*, *598*, 126246. https://doi.org/10.1016/j.jhydrol.2021.126246

Hawkins, T. W., & Woltemade, C. J. (2021). Impact of projected 21st century climate change on basin hydrology and runoff in the Delaware River Basin, USA. *Journal of Water and Climate Change*, *12*(1), 60–81. https://doi.org/10.2166/wcc.2019.140

He, C., & Andres, S. A. (2011). *Report of Investigations No. 77, Simulation of Groundwater Flow in Southern New Castle County, Delaware*. Newark, Delaware. Delaware Geological Survey. https://udspace.udel.edu/bitstream/handle/19716/5855/RI77.pdf?sequence=1&isAllowed=y

Heath, R. C. (1983). *Basic Ground-Water Hydrology*. U.S. Geological Survey Water-Supply Paper 2220. Washington, D.C. https://doi.org/10.3133/wsp2220

Helsel, D. R., Hirsch, R. M., Ryberg, K. R., Archfield, S. A., & Gilroy, E. J. (2020). *Techniques of Water-Resources Investigation of the United States Geological Survey*. Book 4, Chapter A3: Statistical Methods in Water Resources (version 1.1). Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/tm/04/a03/tm4a3.pdf

Hodges, A. L., Jr. (1984). *Hydrology of the Manokin, Ocean City and Pocomoke aquifers of southeastern Delaware*. Delaware Geological Survey Report of Investigations No. 38. Delaware Geological Survey. http://udspace.udel.edu/handle/19716/3151

Hodges, A. L., Jr. (1985). *National Water Summary 1984 (United States Geological Survey Water-Supply Paper 2275)*. Delaware Ground-Water Resources. Washington, D.C. U. S. Geological Survey. https://doi.org/10.3133/wsp2275

Hutson, S. S., Linsey, K. S., Ludlow, R. A., Reyes, B., & Shourds, J. L. (2016). *Estimated Use of Water in the Delaware River Basin in Delaware, New Jersey, New York, and Pennsylvania, 2010*. Scientific Investigations Report 2015-5142. Reston, Virginia. U.S. Geological Survey. https://doi.org/10.3133/sir20155142

Hyndman, R. J., & Athanasopoulos, G. (2018). *Forecasting: principles and practice* (2nd ed.). OTexts. OTexts.com/fpp2

Kauffman, G. (2011). *Economic Value of the Delaware Estuary Watershed: The Delaware Estuary watershed is the economic engine of the Delaware Valley*. University of Delaware. https://udspace.udel.edu/bitstream/handle/19716/9773/DelEstuaryValueReport.pdf

Kiang, J. E., Flynn, K., Zhai, T., Hummel, P., & Granato, G. (2018). *SWToolbox: A Surface-Water Toolbox for Statistical Analysis of Streamflow Time Series: Chapter 11 of Section A, Statistical Analysis; Book 4, Hydrologic Analysis and Interpretation*. Techniques and Methods 4–A11. Reston, Virginia. U. S. Geological Survey. https://doi.org/10.3133/tm4A11

Kumar, C. P. (2012). Climate Change and Its Impact on Groundwater Resources, *1*(5).

Lacombe, P. J., Carleton, G. B., Pope, D. A., & Rice, D. E. (2009). *Future Water-Supply Scenarios, Cape May County, New Jersey, 2003-2050*. Scientific Investigations Report 2009-5187. Reston, Virginia. U.S. Geological Survey. https://doi.org/10.3133/sir20095187

Leopold, L. B., & Langbein, W. B. (1960). *A Primer on Water*. Washington, D.C. U.S. Geological Survey. https://pubs.usgs.gov/gip/7000045/report.pdf

Linsley, R. K., Paulhus, J. L. H., & Kohler, M. A. (1949). *Applied hydrology* (1. ed.). *McGraw-Hill civil engineering series*. McGraw-Hill.

Mann, H. B. (1945). Nonparametric Tests Against Trend. *Econometrica*, *13*(3), 245. https://doi.org/10.2307/1907187

Matalas, N. C. (1963). *Probability Distribution of Low Flows*. Geological Survey Professional Paper 434-A. Washington, D.C. U.S. Geological Survey. https://pubs.usgs.gov/pp/0434a/report.pdf

McCabe, G. J., & Wolock, D. M. (2020). Hydro-Climatic Drought in the Delaware River Basin. *JAWRA Journal of the American Water Resources Association*, *56*(6), 981–994. https://doi.org/10.1111/1752-1688.12875

McLeod, A. (2022). *{Kendall} Kendall-package: Kendall correlation and trend tests*. R package version 2.2.1. https://CRAN.R-project.org/package=Kendall

NJ Highlands. (2008). *Water Resources Volume II Water Use and Availability (Appendix D)*. Technical Report. Chester, New Jersey. New Jersey Highlands Council. https://www.nj.gov/njhighlands/master/tr_water_res_vol_2.pdf

NJ, P.L. 2001 c. 165. (2001). *An act requiring the conducting of certain studies and assessments of water resources in the pinelands area and in Cape May county, and making appropriations therefor* (Vol. 1, p. 1175). Trenton, New Jersey. The State Legislature of New Jersey. https://dspace.njstatelib.org//handle/10929/50431

NJAC 7:19. *N.J. Admin. Code § 7:19, Water Supply Allocation Permits rules.* State of New Jersey. https://www.nj.gov/dep/rules/rules/njac7_19.pdf

NJAC 7:19-8.4. *N.J. Admin. Code § 7:19-8.4 - Water Supply Critical Area I.* State of New Jersey. https://www.nj.gov/dep/rules/rules/njac7_19.pdf

NJAC 7:19-8.5. *N.J. Admin. Code § 7:19-8.5 - Water Supply Critical Area II.* State of New Jersey. https://www.nj.gov/dep/rules/rules/njac7_19.pdf

NJAC 7:50. *Pinelands Comprehensive Management Plan.* State of New Jersey. https://www.nj.gov/pinelands/cmp/CMP.pdf

NJDEP. (2007). *Surficial Geology of New Jersey, 1:100,000, DGS07-2, Edition 200708*. Digital Geologic Series DGS07-2 (GIS Shapefile). New Jersey Department of Environmental Protection (NJDEP), New Jersey Geological Survey (NJGS). https://gisdata-njdep.opendata.arcgis.com/datasets/njdep::surficial-geology-of-new-jersey/about

NJDEP. (2017). *New Jersey Water Supply Plan 2017-2022.* New Jersey Department of Environmental Protection (NJDEP). http://www.nj.gov/dep/watersupply/wsp.html

NJDEP. (2019). *Bedrock Geology for New Jersey 1:100,000*. Series DGS04-6, Edition 20070510 (Geol_bedrock_geology) (Web Mercator ArcGIS Online Service). NJ Department of Environmental Protection. https://www.arcgis.com/home/item.html?id=b44ba71ba8f14ddca3fa8c80bfded0a8

NJDEP. (2020). *New Jersey Scientific Report on Climate Change.* New Jersey Department of Environmental Protection (NJDEP).

NYSDEC. (1990). *Division of Water Technical and Operational Guidance Series (2.1.3. PRIMARY AND PRINCIPAL AQUIFER DETERMINATIONS*. Albany, New York. New York State Department of Environmental Conservation. https://www.dec.ny.gov/docs/water_pdf/togs213.pdf

NYSDEC. (2022). *Unconsolidated Aquifers in Upstate New York* [1:24,000 scale online interactive maps]. New York State Department of Environmental Conservation. https://ny.water.usgs.gov/projects/bgag/aquifer.maps/aquifer1.maps.html

Ouarda, T. B., Charron, C., & St-Hilaire, A. (2008). Statistical Models and the Estimation of Low Flows. *Canadian Water Resources Journal*, *33*(2), 195–206. https://doi.org/10.4296/cwrj3302195

PA DCNR. (2001). *Bedrock Geology of Pennsylvania*. GIS Shapefile (1:250,000 scale). Harrisburg, Pennsylvania. Pennsylvania Bureau of Topographic and Geologic Survey, Dept. of Conservation and Natural Resources. https://www.pasda.psu.edu/uci/DataSummary.aspx?dataset=480

PA DCNR. (2008). *Physiographic Sections*. (GIS Shapefile). Pennsylvania Bureau of Topographic and Geologic Survey, Dept. of Conservation and Natural Resources. https://www.pasda.psu.edu/uci/DataSummary.aspx?dataset=1154

PA DCNR. (2016). *Bedrock Geology of Pennsylvania - Faults (vector)*. GIS Shapefile (1:250,000 scale). Harrisburg, Pennsylvania. Pennsylvania Bureau of Topographic and Geologic Survey, Dept. of Conservation and Natural Resources. https://newdata-dcnr.opendata.arcgis.com/datasets/DCNR::bedrock-geology-of-pennsylvania-faults-vector/about

PADEP. (2009a). *Pennsylvania State Water Plan*. Harrisburg, Pennsylvania. Pennsylvania Department of Environmental Protection. http://files.dep.state.pa.us/Water/Division%20of%20Planning%20and%20Conservation/StateWaterPlan/StateWaterPlanPrinciples/3010-BK-DEP4222.pdf

PADEP. (2009b). *Supporting Documentation: Brodhead Creek, Monroe and Pike Counties, Nomination for Critical Water Planning Area Under Pennsylvania State Water Plan.* Pennsylvania Department of Environmental Protection.

PADEP. (2009c). *Supporting Documentation: Little Lehigh Creek, Lehigh and Berks Counties, Nomination for Critical Water Planning Area Under Pennsylvania State Water Plan.* Pennsylvania Department of Environmental Protection.

PADEP. (2009d). *Supporting Documentation: Neshaminy Creek Tributaries, Montgomery and Buck Counties, Nomination for Critical Water Planning Area Under Pennsylvania State Water Plan.* Pennsylvania Department of Environmental Protection.

PADEP. (2010). *DRAFT Meeting Summary*. Statewide Water Resources Committee. Pennsylvania Department of Environmental Protection. https://files.dep.state.pa.us/PublicParticipation/Advisory%20Committees/AdvCommPortalFiles/SWP/MeetingMinutes/Statewide/2010-11-18DraftMtgSum.pdf

Parker, G. G., Hely, A. G., Keighton, W. B., & Olmsted, F. H. (1964). *Water resources of the Delaware River basin*. Professional Paper 381. U.S. Geological Survey. https://doi.org/10.3133/pp381

Pebesma, E. (2018). {sf} Simple Features for R: Standardized Support for Spatial Vector Data. *The R Journal*, *10*(1), 439--446. https://doi.org/10.32614/RJ-2018-009

Pinelands. (2003). *The Kirkwood-Cohansey Project Work Plan*. New Lisbon, New Jersey. Pinelands Commission. https://www.nj.gov/pinelands/infor/broch/Kirkwood-Cohansey%20Project%20Work%20Plan.pdf

PL 87-328, 75 Stat. 688. (1961, September 27). *Delaware River Basin Compact*. https://www.state.nj.us/drbc/library/documents/compact.pdf

Pope, J. P., Andreasen, D. C., Mcfarland, E. R., & Watt, M. K. (2016). *Digital Elevations and Extents of Regional Hydrogeologic Units in the Northern Atlantic Coastal Plain Aquifer System From Long Island, New York, to North Carolina*. Data Series 996 (ver. 1.1, December 2020). U.S. Geological Survey. https://doi.org/10.3133/ds996

Powell, J. W. (1895). *National Geographic monographs*. No. 2, Physiographic features. National Geographic Society (U.S.).

Pristas, R. S. (2002). *Physiographic Provinces of New Jersey*. Digital Geologic Series DGS02-7 (GIS Shapefile). Trenton, New Jersey. New Jersey Department of Environmental Protection (NJDEP), New Jersey Geological Survey (NJGS). https://www.state.nj.us/dep/njgs/geodata/dgs02-7.htm

Pub. L. No. 90-542, 82 Stat. 906. (1968, October 2). *Wild and Scenic Rivers Act*. https://www.nps.gov/parkhistory/online_books/anps/anps_6f.htm

R Core Team. (2022). *R: A Language and Environment for Statistical Computing*. Vienna, Austria. https://www.R-project.org/

Ramsey, K. W. (2007). *Geologic Map of Kent County, Delaware*. Newark, Delaware. Delaware Geological Survey. https://www.dgs.udel.edu/publications/gm14-geologic-map-kent-county-delaware

Riggs, H. (1968a). *Techniques of Water-Resources Investigation of the United States Geological Survey*. Book 4, Chapter A1: Some Statistical Tools in Hydrology. Washington, D.C. U.S. Geological Survey. https://pubs.usgs.gov/twri/twri4a1/pdf/twri_4-A1_a.pdf

Riggs, H. (1968b). *Techniques of Water-Resources Investigation of the United States Geological Survey*. Book 4, Chapter A2: Frequency Curves. Washington, D.C. U.S. Geological Survey. https://pubs.usgs.gov/twri/twri4a2/pdf/twri_4-A2_a.pdf

Schreffler, C. L. (1996). *Water-use analysis program for the Neshaminy Creek basin, Bucks and Montgomery counties, Pennsylvania: Water-Resources Investigations Report 96-4127, Prepared* *in cooperation with the Delaware River Basin Commission*. Lemoyne, Pennsylvania. U.S. Geological Survey. https://doi.org/10.3133/wri964127

Schreffler, C. L., McManus, B. C., Rowland-Lesitsky, C. J., & Sloto, R. A. (1994). *Hydrologic Data for Northern Bucks County, Pennsylvania*. Open-File Report 94-381. Lemoyne, Pennsylvania. U. S. Geological Survey. https://pubs.usgs.gov/of/1994/0381/report.pdf

Sen, P. K. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Slack, J. R., & Landwehr, J. M. (1992). *Hydro-climatic data network (HCDN); a U.S. Geological Survey streamflow data set for the United States for the study of climate variations, 1874-1988*. Open-File Report 92-129 (Open-File Report). U.S. Geological Survey. https://doi.org/10.3133/ofr92129

Sloto, R. A., & Buxton, D. E. (2005). *Water Budgets for Selected Watersheds in the Delaware River Basin, Eastern Pennsylvania and Western New Jersey*. Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/sir/2005/5113/sir2005-5113.pdf

Sloto, R. A., & Buxton, D. E. (2006). *Estimated Ground-Water Availability in the Delaware River Basin, 1997-2000*. Scientific Investigations Report 2006-5125--Version 1.1. Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/sir/2006/5125/pdf/sir2006-5125_ver1.1.pdf

Sloto, R. A., & Crouse, M. Y. (1996). *HYSEP: A Computer Program for Streamflow Hydrograph Separation and Analysis*. Water-Resources Investigations Report 96-4040. Lemoyne, Pennsylvania. U. S. Geological Survey. https://water.usgs.gov/software/HYSEP/code/doc/hysep.pdf

Sloto, R. A., DeWayne Cecil, L., & Senior, L. A. (1991). *Hydrology and Ground-water Flow in the Carbonate Rocks of the Little Lehigh Creek Basin, Lehigh County, Pennsylvania*. Water-Resources Investigations Report 90-4076. Lemoyne, Pennsylvania. U.S. Geological Survey. https://pubs.er.usgs.gov/publication/wri904076

Sloto, R. A., & Schreffler, C. L. (1994). *Hydrogeology and Ground-water Quality of Northern Bucks County, Pennsylvania*. Water-Resource Investigations Report 94-4109. Lemoyne, Pennsylvania. U. S. Geological Survey. https://pubs.usgs.gov/wri/1994/4109/report.pdf

Spitz, F. J. (2009). *Analysis of Effects of 2003 and Full-Allocation Withdrawals in Critical Area 1, East-Central New Jersey*. Open-File Report 2009-1104. Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/of/2009/1104/pdf/ofr2009-1104.pdf

Spitz, F. J., & dePaul, V. T. (2008). *Recovery of Ground-Water Levels from 1988 to 2003 and Analysis of Effects of 2003 and Full-Allocation Withdrawals in Critical Area 2, Southern New Jersey*. Scientific Investigations Report 2008–5142. Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/sir/2008/5142/pdf/sir2008-5142.pdf

Spitz, F. J., Watt, M. K., & dePaul, V. T. (2007). *Recovery of Ground-Water Levels From 1988 to 2003 and Analysis of Potential Water-Supply Management Options in Critical Area 1, East-Central New Jersey*. Scientific Investigations Report 2007–5193. Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/sir/2007/5193/pdf/sir2007-5193.pdf

Stanford, S. D. (2004). *Surficial Geology of the Camden and Philadelphia Quadrangles, Camden, Gloucester, and Burlington Counties, New Jersey*. Open File Map OFM 60. U.S. Geological Survey. https://www.nj.gov/dep/njgs/pricelst/ofmap/ofm60.pdf

Stuckey, M. H. (2006). *Low-Flow, Base-Flow, and Mean-Flow Regression Equations for Pennsylvania Streams*. Scientific Investigations Report 2006-5130. Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/sir/2006/5130/

Stuckey, M. H. (2008). *Development of the Water-Analysis Screening Tool Used in the Initial Screening for the Pennsylvania State Water Plan Update of 2008*. Open-File Report 2008–1106. Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/of/2008/1106/pdf/ofr2008-1106.pdf

Sumner, D. M., Nicholson, R. S., & Clark, K. L. (2012). *Measurement and Simulation of Evapotranspiration at a Wetland Site in the New Jersey Pinelands*. Scientific Investigations Report 2012–5118.

Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/sir/2012/5118/pdf/sir2012-5118.pdf

Sundstrom, R. W., & Pickett, T. E. (1971). *The availability of ground water in New Castle County, Delaware.* University of Delaware, Water Resources Center.

Taylor, C. J., & Alley, W. M. (2001). *Ground-Water-Level Monitoring and the Importance of Long-Term Water-Level Data*. U.S. Geological Survey Circular 1217. Denver, Colorado. U.S. Geological Survey. https://pubs.usgs.gov/circ/circ1217/

Taylor, F. H. (1895). *The Hand Book of the Lower Delaware River: Ports, Tides, Pilots, Quarantine Stations, Light-house Service, Life-saving and Maritime Reporting Stations*. G.S. Harris & Sons, printers.

Theil, H. (1950). A rank-invariant method of linear and polynominal regression analysis (Parts 1-3). *Proceedings of the Royal Netherlands Academy of Sciences*, *53*, Part I: 386-392, Part II: 521-525, Part III: 1397-1412.

Thompson, M. Y., & Pindar, C. E. (2021). *Water Withdrawal and Consumptive Use Estimates for the Delaware River Basin (1990-2017) With Projections Through 2060*. DRBC Report No: 2021-4. West Trenton, New Jersey. Delaware River Basin Commission. https://www.nj.gov/drbc/library/documents/water-use/DRBC_2021-4_Water2060_Final_101421.pdf

USACE. (2006). *Groundwater Model Production Run report, Upper New Castle County, Delaware*. report prepared for the Delaware Department of Natural Resources and Environmental Control. U.S. Army Corps of Engineers, Philadelphia District.

USACE & DRBC. (2008). *Enhancing Multi-jurisdictional Use and Management of Water Resources for the Delaware River Basin, NY, NJ, PA, and DE*. West Trenton, New Jersey. USACE Philadelphia District and the Delaware River Basin Commission. https://www.nj.gov/drbc/about/public/multi-juris-study.html

USGS. (1998). *Southeastern Pennsylvania ground water protected area: Open-File Report 98-571* (Open-File Report). U.S. Geological Survey. https://doi.org/10.3133/ofr98571

USGS. (2008). *Water-capacity analysis of New Jersey HUC11 watersheds: un-published report by the U.S. Geological Survey New Jersey Science Center*. On file with the N.J. Department of Environmental Protection, Division of Water Supply and Geosciences. West Trenton, New Jersey. U.S. Geological Survey.

USGS. (2013). *Water Basics Glossary*. https://water.usgs.gov/water-basics_glossary.html

USGS. (2022). *National Water Information System (NWIS)*. accessed April 5, 2022. U.S. Geological Survey. http://nwis.waterdata.usgs.gov/nwis

Walker, R. L., Nicholson, R. S., & Storck, D. A. (2011). *Hydrologic Assessment of Three Drainage Basins in the Pinelands of Southern New Jersey, 2004–06*. Scientific Investigations Report 2011–5056. Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/sir/2011/5056/pdf/sir20115056.pdf

Walker, R. L., Reilly, P. A., & Watson, K. M. (2008). *Hydrogeologic Framework in Three Drainage Basins in the New Jersey Pinelands, 2004-06*. Scientific Investigations Report 2008-5061. Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/sir/2008/5061/pdf/sir2008-5061.pdf

Watson,, K. M., Reiser,, R. G., Nieswand,, S. P., & Schopp, R. D [Robert D.]. (2005). *Streamflow Characteristics and Trends in New Jersey, Water Years 1897–2003*. Scientific Investigations Report 2005-5105. Reston, Virginia. U.S. Geological Survey. https://pubs.usgs.gov/sir/2005/5105/

Weibull, W. (1939). A Statistical Theory of the Strength of Materials. *The Swedish Academy of Sciences' Documents (Vetenskapsakademiens Handlingar)*, *151*.

Wherry, E. T., Stose, G. W., Jonas, A., Bliss, E., & Blscom, F. (1931). *Geologic Map and Sections of the Quakertown and Doylestown Quadrangles, Pennsylvania-New Jersey*. USGS Bulletin 828, Plate 1. U.S. Geological Survey. https://digital.libraries.psu.edu/digital/collection/pageol/id/52148/

White, K. E., & Sloto, R. A. (1990). *Base-flow-frequency characteristics of selected Pennsylvania streams*. Water-Resources Investigations Report 90-4160. Harrisburg, Pennsylvania. U.S. Geological Survey. https://doi.org/10.3133/wri904160

Williamson, T. N., Nystrom, E. A., & Milly, P. C. D. (2016). Sensitivity of the projected hydroclimatic environment of the Delaware River basin to formulation of potential evapotranspiration. *Climatic Change*, *139*(2), 215–228. https://doi.org/10.1007/s10584-016-1782-2

Zapecza, O. S. (1989). *Hydrologic Framework ok the New Jersey Coastal Plain; Regional Aquifer-System Analysis*. U.S. Geological Survey Professional Paper 1404-B. Washington, D.C. U.S. Geological Survey. https://doi.org/10.3133/pp1404B

Glossary Disclaimer

This report is not a rule, regulation or guidance and has no legal significance. Although certain definitions in this Glossary are derived from the Delaware River Basin Compact and implementing regulations, all definitions, regardless of their sources, are provided solely to assist readers in understanding the data and other information presented herein.

11. GLOSSARY

Aquifer: A waterbearing formation that contains sufficient ground water to be important as a source of supply (18 CFR §430.5).

Basin: The area of drainage into the Delaware River and its tributaries, including Delaware Bay (PL 87-328, 75 Stat. 688, §1.2 a). *Synonymous with Delaware River Basin, unless specified otherwise*

Baseflow: The sustained low flow of a stream, usually ground-water inflow to the stream channel; the amount of water carried in a stream or river that comes from ground water sources (DRBC, 1981; USGS, 2013).

Bedrock: A general term used for solid rock that underlies soils or other unconsolidated material (USGS, 2013).

Carbonate rocks: Rocks (such as limestone or dolostone) that are composed primarily of minerals (such as calcite and dolomite) containing the carbonate ion (CO_3^{2-}) (USGS, 2013).

Commission: The Delaware River Basin Commission created and constituted by the Compact (PL 87-328, 75 Stat. 688, §1.2 b). *Synonymous with Delaware River Basin Commission (DRBC)*

Compact: Defined as Part I of Public Law 87-328 (PL 87-328, 75 Stat. 688, §1.2 c). *Synonymous with Delaware River Basin Compact*

Comprehensive Plan: The plans, policies and programs adopted as part of the Comprehensive Plan of the Delaware Basin in accordance with section 3.2 and Article 13 of the Delaware River Basin Compact (18 CFR §430.5).

Confined aquifer (artesian aquifer): An aquifer that is completely filled with water under pressure and that is overlain by material that restricts the movement of water (USGS, 2013).

Crystalline rocks: Rocks (igneous or metamorphic) consisting wholly of crystals or fragments of crystals (USGS, 2013).

Consumptive use: The water lost due to transpiration from vegetation in the building of plant tissue, incorporated into products during their manufacture, lost to the atmosphere from cooling devices, evaporated from water surfaces, exported from the Delaware River Basin, or any other water use for which the water withdrawn is not returned to the surface waters of the Basin undiminished in quantity (18 CFR §420.1 d).

Consumptive use ratio (CUR): Is the ratio between the total withdrawal amount, and the portion of the withdrawal which is consumptively used. For specific facilities, a consumptive use ratio may be the result of direct measurement, calculation, estimation, or a "default" value based on the withdrawal category and literature review.

Depletive use: *See also Consumptive use.*

Discharge: The volume of fluid passing a point per unit of time, commonly expressed in cubic feet per second (CFS), million gallons per day, gallons per minute, or seconds per minute per day (USGS, 2013).

Discharge area (ground water): Area where subsurface water is discharged to the land surface, to surface water, or to the atmosphere (USGS, 2013).

Drainage area: The drainage area of a stream at a specified location is that area, measured in a horizontal plane, which is enclosed by a drainage divide (USGS, 2013).

Drainage basin: The land area drained by a river or stream (USGS, 2013).

Drought of Record: The drought of record, which occurred in the period 1961-1967, shall be the basis for determination and planning of dependable Basin water supply (18 CFR 410, §2.400.1).

Effective precipitation (rainfall): 1. That part of the precipitation that produces runoff. 2. A weighted average of current and antecedent precipitation that is "effective" in correlating with runoff (USGS, 2013).

Geology: the study of the planet earth- the materials it is made of, the processes that act on those materials, the products formed, and the history of the planet and its life forms since its origin (USGS, 2013).

Groundwater: All water beneath the surface of the ground (18 CFR §430.5).

Groundwater basin: A subsurface structure having the character of a basin with respect to the collection, retention and outflow of water (18 CFR §430.5).

Groundwater protected area: The areas declared and delineated by the Commission to be a ground water protected area pursuant to Article 10 of the Delaware River Basin Compact and these regulations (18 CFR §430.5).

Groundwater recharge: The entry into the saturated zone of water made available at the water-table surface, together with the associated flow toward the water table within the saturated zone (USGS, 2013).

Hydrology: The science encompassing the behavior of water as it occurs in the atmosphere, on the surface of the ground, and underground (USGS, 2013).

Recharge (groundwater): The process involved in the absorption and addition of water to the zone of saturation; also, the amount of water added (USGS, 2013).

Recharge area (groundwater): An area within which water infiltrates the ground and reaches the zone of saturation (USGS, 2013).

Recurrence interval: The average interval of time within which the magnitude of a given event, such as a storm, flood or low flow event will be equaled or exceeded once (USGS, 2013).

Saltwater intrusion: The migration of saltwater into freshwater aquifers under the influence of groundwater development (USGS, 2013).

Self-supplied: Water users responsible for their own sources of supply, e.g., a residential dwelling with its own well, or an industry with its own water intake.

Signatory party: A state or commonwealth party to the Compact, and the federal government (PL 87-328, 75 Stat. 688, §1.2 h).

Sourcewater: An aquifer or surface water body from which water is taken either periodically or continuously for off-stream uses.

Southeastern Pennsylvania Groundwater Protected Area (SEPA-GWPA): The Southeastern Pennsylvania Groundwater Protected Area consists of those portions of the listed counties and political subdivision located within the Delaware Basin, as outlined in 18 CFR §430.7(a).

Subbasin: A drainage area subdivision that forms a convenient natural unit for purposes of resource management. *See also Groundwater basin, see also Watershed*

Surface water: An open body of water such as a lake, river, or stream.

Unconfined aquifer: An aquifer whose upper surface is a water table free to fluctuate under atmospheric pressure (USGS, 2013).

Water allocation: Generally, a regulated withdrawal of water from a ground or surface source based on total volume and/or rate of withdrawal. This term is also applied to designated amounts of storage in a reservoirs and conservation releases. This term is not to be confused with the terms load allocation or waste load allocation which are permitted discharges regulated as part of a TMDL.

Water resources: Includes water and related natural resources in, on, under, or above the ground, including related uses of land, which are subject to beneficial use, ownership or control (PL 87-328, 75 Stat. 688, §1.2 i).

Water supply: This term is typically used to describe the sum of all water sources available for use. It can be understood in the context of balancing available water supply (what we have) with water demand (what we want). It is distinct from the term Public Water Supply that refers to a specific category of water use.

Water use: Refers broadly to withdrawals (water which is either withdrawn or diverted for any purpose) and/or the end-use of water (the point at which water is consumed or used). *See also Withdrawal, See also End-use*

Water use category: A category assigned to the end-use of water after it is withdrawn.

Water user: Any person, corporation, partnership, association, trust, or other entity, public or private who uses, takes, withdraws or diverts surface waters within the Delaware River Basin (18 CFR §420.1 a-b).

Watershed: The total area above a given point on a watercourse that contributes water to its flow; the entire region drained by a waterway or watercourse that drains into a lake, reservoir or bay.

Withdrawal (water): Water withdrawn from its source for any purpose. *See also Water use*

Withdrawal category: A category assigned to withdrawal sources which describe the source/facility performing the withdrawal (and not necessarily the end use of water).

Withdrawal sector: A group of common withdrawal categories for the purposes of planning and data management.

Withdrawal sector (Industrial): Water withdrawals by facilities associated with fabrication, processing, washing, and cooling. This sector includes industries such as chemical and allied products, food, paper and allied products, petroleum refining (i.e., refineries), and steel. Due to the generally close relationship, water withdrawn for groundwater remediation purposes are also included in this sector. However, this sector does not include withdrawals associated with commercial, mining, or power generation facilities (including cogeneration facilities).

Withdrawal sector (Irrigation): Water withdrawals which are applied by an irrigation system to assist crop and pasture growth, or to maintain vegetation on recreational lands such as parks and golf courses. Irrigation includes water that is applied for pre-irrigation, frost protection, chemical application, weed control, field preparation, crop cooling, harvesting, dust suppression, leaching of salts from the root zone, and conveyance losses. This sector does not include withdrawals/ diversions associated with aquaculture.

Withdrawal sector (Mining): Water withdrawals by facilities involved with the extraction of naturally occurring minerals. This sector includes operations such as mine dewatering, quarrying, milling of mined materials, material washing and processing, material slurry operations (e.g., sand), dust suppression and any other use at such facilities.

Withdrawal sector (Other): This sector includes all other categories of withdrawals not captured by the industrial, irrigation, mining, public water supply or power generation sectors. This sector includes facilities which may be classified as aquaculture, bottled water, commercial (e.g., hotels, restaurants, office buildings, retail stores), fire suppression, hospital/health, military, parks/recreation, prisons, schools, and ski/snowmaking.

Withdrawal sector (Power Generation): Water withdrawn/diverted by facilities associated with the process of generating electricity. Within the Delaware River Basin, this sector refers to water withdrawn/diverted by both thermoelectric (including cogeneration) and hydroelectric facilities. Thermoelectric withdrawals may include both water and reclaimed wastewater, and are typically used for cooling purposes. Hydroelectric facility water diversions are typically used as the primary mover for power generation.

Withdrawal sector (Public Water Supply): Water withdrawn by a facility meeting the definition of a public water supply system under the Safe Drinking Water Act (P.L. 93-523, 88 Stat. 1660), or subsequent regulations set forth by signatory parties.

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APPENDICES

Appendix A: Subbasin Names

Table A-1: Appendix Table 1: Names of 147 subbasins

Basin ID	Basin Name
DB-001	Upper West Branch Delaware River
DB-002	Little Delaware River
DB-003	Middle part of West Branch Delaware River
DB-004	Upper part of West Branch Delaware River and East Branch Delaware River
DB-005	Lower part West Branch Delaware River
DB-006	Cold Spring Creek, Butler Brook, Bone Creek
DB-007	Oquaga Creek
DB-008	Whitaker Brook, Rhoads Creek, Cadosia Creek, City Brook, Read Creek (tributaries to Delaware River)
DB-009	Faulkner Brook, Balls Creek, Shehawken Creek, Sherman Creek
DB-010	Upper part of East Branch Delaware River above Platte Kill
DB-011	Upper part East Branch Delaware River and tributaries to Pepacton Reservoir
DB-012	Upper part of Beaver Kill
DB-013	Willowemoc Creek
DB-014	Middle part of East Branch Delaware River below Pepacton Reservoir
DB-015	Lower part of Beaver Kill
DB-016	Lower part East Branch Delaware River
DB-017	Hankins Creek, Basket Creek, Hoolihan Creek, Abe Lord Creek, Humphries Creek, Blue Mill Stream (tributaries to Delaware River)
DB-018	Equinunk Creek
DB-019	East Branch Callicoon Creek
DB-020	North Branch Callicoon Creek
DB-021	Unnamed tributaries to Delaware River
DB-022	Caulkins Creek, Cooley Creek, Hollister Creek, Beaverdam Creek, Peggy Run (tributaries to Delaware River)
DB-023	Ten Mile River
DB-024	Masthope Creek, Westcolong Creek (tributaries to Delaware River)
DB-025	West Branch Lackawaxen River
DB-026	Dyberry Creek
DB-027	Middle Creek
DB-028	Lackawaxen River
DB-029	Fish Cabin Creek, Mill Brook, Halfway Brook, Beaver Brook, Narrow Falls Brook, Grassy Swamp Brook (tributaries to Delaware River)
DB-030	West Branch Wallenpaupack Creek
DB-031	Wallenpaupack Creek
DB-032	Shohola Creek, Panther Creek (tributaries to Delaware River)
DB-033	Mongaup River above Swinging Bridge Reservoir
DB-034	Mongaup River tributaries to Swinging Bridge Reservoir
DB-035	Mongaup River below Swinging Bridge Reservoir, Shingle Kill
DB-036	Walker Lake Creek, Pond Eddy Creek, Cummins Creek, Sawkill Creek, Crawford Brook (tributaries to Delaware River)
DB-037	Neversink River above Neversink Reservoir
DB-038	Neversink River below Neversink Reservoir
DB-039	Basher Kill
DB-040	Raymondskill Creek, Dingmans Creek, Conashaugh Creek, Dry Brook, Adams Creek, Hornbecks Creek, Toms Creek (tributaries to Delaware River)

Basin ID	Basin Name
DB-041	Unnamed tributary to Delaware River
DB-042	Flat Brook
DB-043	Bush Kill
DB-044	Vancampens Brook, Dunnfield Creek, and tributaries to Delaware River
DB-045	Brodhead Creek
DB-046	Pocono Creek
DB-047	Cherry Creek, Caledonia Creek (tributaries to Delaware River)
DB-048	Slateford Creek, Jacoby Creek, Allegheny Creek (tributaries to Delaware River)
DB-049	Paulins Kill above Stillwater Village, Trout Brook
DB-050	Paulins Kill below Stillwater Village
DB-051	Stony Brook, Delawanna Creek, Beaver Brook
DB-052	Pequest River
DB-053	Martins Creek, Mud Run (tributaries to Delaware River)
DB-054	Pophandusing Brook, Buckhorn Creek, Lopatcong Creek, and tributaries to Delaware River
DB-055	Bush Kill
DB-056	Upper part of Lehigh River
DB-057	Tobyhanna Creek
DB-058	Bear Creek
DB-059	Middle part of Lehigh River above Sandy Run
DB-060	Middle part of Lehigh River above Black Creek
DB-061	Middle part of Lehigh River above Pohopoco Creek
DB-062	Pohopoco Creek
DB-063	Lower part of Lehigh River
DB-064	Aquashicola Creek
DB-065	Lower part of Lehigh River above Little Lehigh Creek
DB-066	Jordan Creek
DB-067	Little Lehigh Creek
DB-068	Lower part of Lehigh River below Little Lehigh Creek
DB-069	Pohatcong Creek
DB-070	Musconetcong River above Trout Brook
DB-071	Musconetcong River below and including Trout Brook
DB-072	Frya Run, Cooks Creek, Tinicum Creek, and tributaries to Delaware River
DB-073	Harihokake Creek, Nishisakawick Creek, and tributaries to Delaware River
DB-074	Tohickon Creek
DB-075	Lockatong Creek, Wickecheoke Creek, and tributaries to Delaware River
DB-076	Geddes Run, Hickory Creek, Paunacussing Creek, Aquetong Creek, Hollow Run, Pidock Creek, Jericho Creek, Houghs Creek, Dyers Creek
DB-077	Alexauken Creek, Moores Creek, Jacobs Creek, and tributaries to Delaware River
DB-078	Assunpink Creek
DB-079	Martins Creek, and tributaries to Delaware River
DB-080	Crosswicks Creek
DB-081	Crafts Creek, Blacks Creek, and tributaries to Delaware River
DB-082	Assiscunk Creek and tributaries to Delaware River
DB-083	Neshaminy Creek above Little Neshaminy Creek
DB-084	Neshaminy Creek below Little Neshaminy Creek
DB-085	North Branch Rancocas Creek above New Lisbon dam, Greenwood Brook
DB-086	South Branch Rancocas Creek above Bobbys Run
DB-087	South Branch Rancocas Creek above South West Branch
DB-088	Rancocas Creek main stem with North Branch below New Lisbon dam and South Branch below Bobbys Run
DB-089	Poquessing Creek, Pennypack Creek, and tributaries to Delaware River
DB-090	Pennsauken Creek, Pompeston Creek, and tributaries to Delaware River
DB-091	Frankford Creek and tributaries to Delaware River

Basin ID	Basin Name
DB-092	Cooper River
DB-093	Woodbury Creek, Big Timber Creek, Newton Creek, and tributaries to Delaware River
DB-094	Little Schuylkill River
DB-095	Upper part of Schuylkill River above Pottsville
DB-096	Upper part of Schuylkill River below Pottsville
DB-097	Tributaries to middle part of Schuylkill River
DB-098	Maiden Creek above Saucony Creek
DB-099	Maiden Creek below Saucony Creek
DB-100	Upper Tulpehocken Creek above Blue Marsh Reservoir
DB-101	Lower Tulpehocken Creek below Blue Marsh Reservoir
DB-102	Tributaries to Lower Middle Schuylkill River
DB-103	Manatawny Creek
DB-104	Lower part of Schuylkill River and tributaries above Skippack Creek
DB-105	French Creek
DB-106	West Branch Perkiomen Creek
DB-107	Perkiomen Creek above and including East Branch
DB-108	Perkiomen Creek below East Branch
DB-109	Lower part of Schuylkill River and tributaries below Skippack Creek
DB-110	Wissahickon Creek
DB-111	Mantua Creek
DB-112	Darby Creek
DB-113	Cedar Swamp, Repaupo Creek, Clonmell Creek, and tributaries to Delaware River
DB-114	Crum Creek, Ridley Creek, Marcus Hook Creek
DB-115	Chester Creek
DB-116	Naamans Creek, Shellpot Creek and tributaries to Delaware River
DB-117	Raccoon Creek & Birch Creek
DB-118	Oldmans Creek
DB-119	Salem River above dam, Salem Canal, and tributaries to Delaware Bay
DB-120	East Branch Brandywine Creek
DB-121	West Branch Brandywine Creek
DB-122	Brandywine Creek (main stem)
DB-123	Red Clay Creek
DB-124	White Clay Creek
DB-125	Christina River and tributaries to Delaware River
DB-126	Salem River below dam and tributaries to Delaware Bay
DB-127	Army Creek, Red Lion Creek, Dragon Creek, and tributaries to Delaware River
DB-128	C and D Canal and tributaries to Delaware Bay
DB-129	Alloway Creek, Hope Creek, and tributaries to Delaware Bay
DB-130	Augustine Creek, Appoquinimik River, Blackbird Creek, and tributaries to Delaware Bay
DB-131	Stow Creek and tributaries to Delaware Bay
DB-132	Smyrna River, Duck Creek, Mill Creek and tributaries to Delaware Bay
DB-133	Cohansey River
DB-134	Back Creek, Cedar Creek, Nantuxent Creek, Dividing Creek and tributaries to Delaware Bay
DB-135	Leipsic River, Simons River, Little River, and tributaries to Delaware Bay
DB-136	Scotland Run, Still Run, & Little Ease Run
DB-137	Maurice River above Sherman Ave Bridge & Muddy Run
DB-138	Maurice River above Menantico Creek
DB-139	Menantico Creek, Manamuskin River
DB-140	Maurice River below Menantico Creek
DB-141	West Creek, East Creek, Dennis Creek, and tributaries to Delaware Bay
DB-142	Tributaries to Delaware Bay
DB-143	Saint Jones River
DB-144	Murderkill River

Basin ID	Basin Name
DB-145	Mispillion River and tributaries to Delaware Bay
DB-146	Cedar Creek, Slaughter Creek, Primehook Creek, & tributaries to Delaware Bay
DB-147	Round Pole Branch and tributaries to Delaware Bay

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