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Evaluation of reported and unreported water uses in various sectors of the Potomac basin for the year 2017

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Abstract

Water resource planners and managers in the Mid-Atlantic United States typically determine the sufficiency of water supplies to meet demand by comparing (1) water use as reported to the state by individual water users to (2) metrics of water availability calculated from observed water monitoring networks. This paper focuses on determining whether this means of measuring water use is sufficient for proactive and sustainable management of water resources. The Potomac basin study area illustrates the point that, while state-reported water use databases typically cover the largest individual water users, unreported water uses can cumulatively comprise a substantial portion of the overall water use. If left unaccounted for, the system is vulnerable to human demand exceeding supplies, with attendant detrimental effects to aquatic habitats and organisms, especially given the exacerbating effects of climate change on the variability of water supplies. Planners and managers are therefore encouraged to consider the full spectrum of water uses, regardless of state reporting requirements.

KEYWORDS
watershed management, water resources management, water use, water withdrawal, unreported water withdrawal, Potomac basin, Mid-Atlantic United States, water use estimation, water demand assessment

1 | INTRODUCTION

Understanding human water use in a river basin is a foundational component of sustainable environmental resources management. Developing a thorough picture of water use leads to more informed management decisions at the local and regional levels by shedding light on system vulnerabilities such as inadequate water availability and environmental impacts. This is particularly important in the Potomac basin because it is home to the nation's capital and nearly seven million people and encompasses diverse natural and living resources.

In 2018, the Interstate Commission on the Potomac River Basin (ICPRB) completed a Potomac Basin Comprehensive Water Resources Plan based on a stakeholder-developed vision (ICPRB, 2018). The plan identified four challenge areas, namely ensuring sustainable water use and supplies; protecting and improving water quality; managing land use for sustainability; and protecting ecological health. A key finding of the

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Research Impact Statement

This research underscores the importance of accounting for both reported and unreported water use in planning efforts, applies methods for estimating unreported water uses for various water use sectors.

planning process was that a complete picture of human water uses in the basin may be lacking. The question was raised whether state water use databases (compiled based on water use reports required under state law) fully or sufficiently capture water use in the major watersheds of the basin. While state-reported water use databases typically cover the largest individual water users, unreported water uses can cumulatively comprise a substantial portion of total water use at the watershed and basin scale. If these are left unaccounted for, the system is vulnerable to human demand exceeding supplies, with detrimental effects to aquatic habitats and organisms, especially given the exacerbating effects of climate change on variability of water supplies. This study was done to address this concern.

It is important to note that this paper focuses on quantifying water withdrawals and does not attempt to quantify the consumptive portion of the withdrawals (e.g., the amount of water withdrawn from the source but not subsequently returned). Consumptive uses will be evaluated in a forthcoming study and will be an essential next step in understanding the water budget in the Potomac basin. In the meantime, previous studies on consumptive use in the Potomac basin are available for reference (Ahmed et al., 2015; USACE et al., 2014).

1.1 | Potomac basin study area

The approximately 14,695 square mile Potomac basin lies in the Mid-Atlantic region of the United States (U.S.). It includes portions of Pennsylvania, Maryland, Virginia, and West Virginia; and the entire District of Columbia. The basin comprises 11 eight-digit watersheds (hydrologic unit codes, or HUC8) across the study area (Figure 1). These HUCs are part of a standardized, national system of delineated watersheds. Table 1 provides the HUC8 codes, names, and areas of these watersheds.

The basin is home to approximately 6.89 million people according to the 2020 U.S. Census with nearly 81% of residents living in urban areas. It is also home to threatened and endangered species such as the Shortnosed sturgeon and Eastern Hellbender (Maryland Natural Heritage Program, 2021). Furthermore, there are species of interest such as the bald eagle, American shad, and blue crabs and areas of special concern such as the Potomac Gorge, including Great Falls, which has "unique and rare riparian biological communities" (USACE et al., 2014).

The Potomac River is the second-largest source of fresh water to the Chesapeake Bay, behind only the Susquehanna River. Compared to other Mid-Atlantic river basins such as the Susquehanna and the Delaware, the Potomac basin is relatively unregulated with comparatively few impoundments and, as a result, is considered a hydrologically flashy system (USACE et al., 2014). In 2012, the Potomac River was named America's Most Endangered River by American Rivers due to water quality threats such as urban runoff, development, and nutrient pollution from farms, the effects of which are expected to be exacerbated by climate change (American Rivers, 2012).

The Potomac basin spans five major physiographic provinces (Fenneman & Johnson, 1946) namely, the Appalachian Plateau, Valley and Ridge, Blue Ridge, Piedmont, and the Coastal Plain (in order from northwest to southeast). The Fall Line roughly falls along the boundary between the Piedmont and the Coastal Plain (Figure 1). The hydrology above and below the Fall Line is different. Below the Fall Line, groundwater resources are present in a confined aquifer system that is recharged through infiltration from overlying aquifers and outcroppings near the Fall Line. Above the Fall Line, groundwater is found in fractured bedrock that is often highly connected to surface water resources and varies with recent meteorological conditions. Differences in the proportions of surface and groundwater use above and below the Fall Line are one result of these unique physical characteristics. Specifically, surface water sources dominate above the Fall Line given the relatively small amount of storage in the groundwater systems while groundwater sources dominate below the Fall Line (ICPRB, 2018).

1.2 | Water use in the Potomac basin

For the first time, this paper presents both reported and unreported water use estimates from four of the basin's five jurisdictions. While the District of Columbia uses water from the Potomac River, water is not withdrawn within its jurisdictional boundaries. Rather, it purchases water from the Washington Aqueduct, whose intake is in Maryland waters, for public water supply purposes. Reported uses from Maryland, Pennsylvania, Virginia, and West Virginia are calculated from data supplied by state water agencies and are a collection of water withdrawal reports from entities that are required to supply such information due to the states' water resource legislation as well as entities that voluntarily submit this information. Unreported uses are those that do not meet state-prescribed reporting thresholds and are not part of any voluntary reporting programs. The four states set their own thresholds as part of the state's unique water resources legislation, which includes the following:

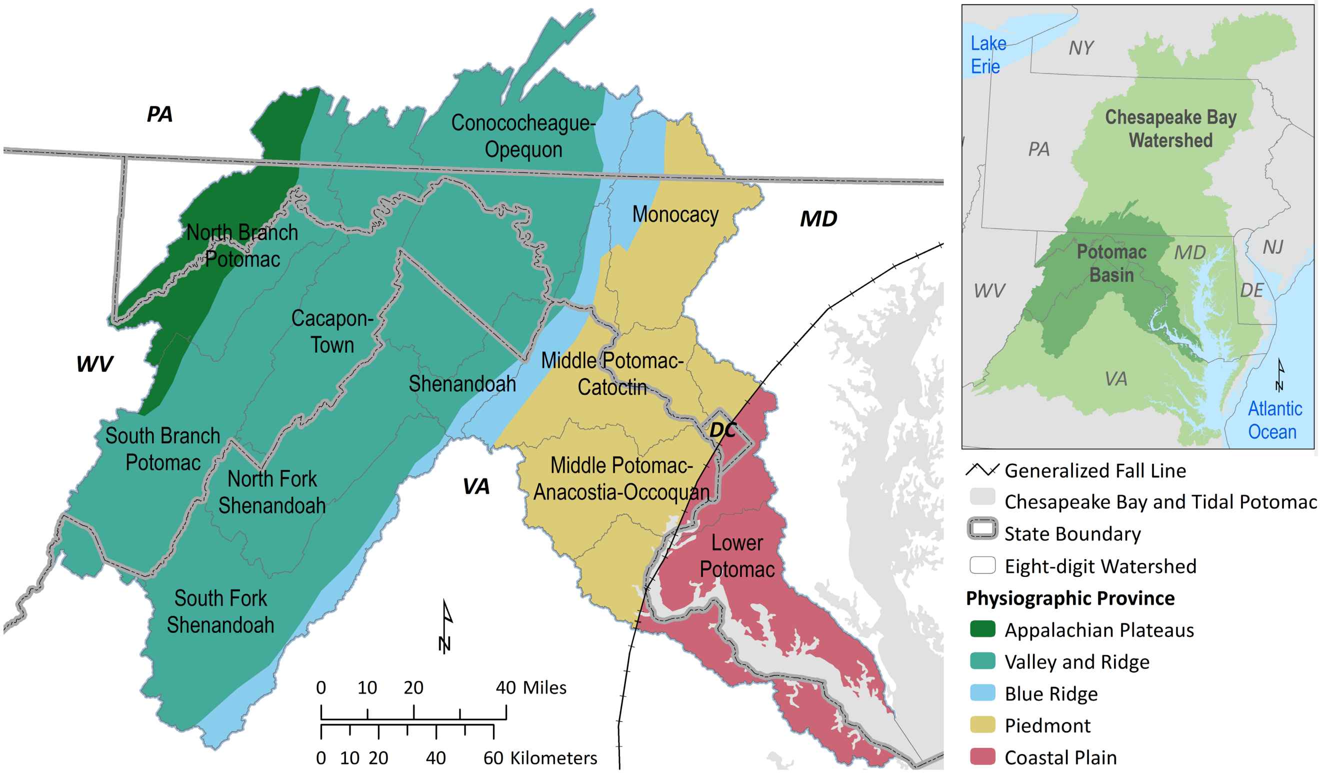

FIGURE 1 Eight-digit watersheds with respect to physiographic provinces and the fall line in the Potomac basin. The inset map shows the location of the Potomac basin in the Chesapeake Bay watershed.

TABLE 1 Area of the eight-digit watersheds within the Potomac basin, from upstream to downstream.

HUC8 code	HUC8 name	Area (square mile)
02070001	South Branch Potomac	742
02070002	North Branch Potomac	673
02070003	Cacapon-Town	603
02070004	Conococheague-Opequon	1139
02070005	South Fork Shenandoah	838
02070006	North Fork Shenandoah	518
02070007	Shenandoah	176
02070008	Middle Potomac-Catoctin	619
02070009	Monocacy	485
02070010	Middle Potomac-Anacostia-Occoquan	652
02070011	Lower Potomac	903
Total		7348

Abbreviation: HUC, hydrologic unit code.

- Maryland: Annotated Code of Maryland, Environment Article, § 5–501 thru § 5-5B-05; COMAR 26.17.06;
- Pennsylvania: Title 25 (Environmental Protection), Chapter 110 (Water Resources Planning) of the Pennsylvania code;
- Virginia: Water Withdrawal Reporting Regulation (9 VAC 25–200, et seq.); and
- West Virginia: Water Resources Protection and Management Act of 2008.

While there are some differences in the state reporting thresholds in the Potomac basin (Palmer & Moltz, 2013), water uses above 10,000 gallons per day (GPD) and all public water supply uses are required to be reported as a general rule of thumb. If water use does not meet the threshold, it is not required to be reported.

By definition, unreported water uses are smaller quantities and, therefore, have been considered to have less of an impact. However, the cumulative impact of the unreported uses may be considerable in geographic areas where they make up a significant portion of the total water use. This has been demonstrated in sub-watersheds of the Potomac basin. For example, in the 143 square miles Marsh and Rock creek sub-watersheds in Adams County, Pennsylvania, unreported water uses made up 44% of the total use as documented in the 2012 Critical Area Resources Plan (Moltz & Palmer, 2012).

Prior to the completion of this study, reported water use summaries along with select, jurisdiction-specific unreported estimates were available through state water planning efforts (PA DEP, 2009; VA DEQ, 2015; WV DEP, 2013); federally through the U.S. Geological Survey's (USGS) National Water Use Information Program (Dieter et al., 2018); and through a previous ICPRB data compilation effort (Ducnuigeen et al., 2015). The study described here applies a consistent methodology across the interstate basin to calculate 2017 reported water uses and estimate unreported water uses. This marks a solid step forward in understanding water use in the hydrologic basin despite jurisdictional boundaries and reporting thresholds.

2 | METHODS

When looking at water use analysis efforts in other basins and jurisdictions, similar efforts to aggregate reported and unreported uses can be found. These include, but are not limited to, the Delaware River Basin Commission (Thompson & Pindar, 2021), Susquehanna River Basin Commission (Balay et al., 2016), Upper Rio Grande Basin (Ivahnenko et al., 2021), and Commonwealth of Virginia (VA DEQ, 2022). Thompson and Pindar (2021) examined the reported water withdrawals within the Delaware River basin by applying a hierarchical model structure to eight water use sectors including public water supply, power generation, industrial, irrigation, mining, out-of-basin diversions, and other sectors. The regulated and unregulated consumptive use (CU) of water was explored in the Susquehanna River basin using a combination of techniques including: (1) a comprehensive basin-wide database of regulated water uses, (2) previously recorded basin-specific CU records supplemented with published CU coefficients, and (3) unregulated water use estimation methods based on available population and agricultural data (Balay et al., 2016). Ivahnenko et al. (2021) estimated water withdrawals and use in the public water supply, domestic, and irrigation sectors by area-weighting county-level reported and estimated unreported withdrawal data from 1985 to 2015 in the Upper Rio Grande basin. Finally, the Commonwealth of Virgina calculates surface and groundwater withdrawals using values reported in water supply plans at the local and regional level, water withdrawal permits, and annual water withdrawal values reported to the state (VA DEQ, 2022). In general, the methods used for compiling and estimating reported and unreported uses are similar to those used here.

Strategies for quantifying reported and unreported water uses necessarily differ. Calculating reported water uses is somewhat straightforward because the states maintain databases of reported water uses. Estimating unreported water uses is more challenging as it requires use of available geospatial datasets and one or more methods for estimating water use rates. This section is divided into two major parts, describing reported uses and the methods used to estimate unreported uses. The estimate of unreported uses was done for the year 2017, so reported uses are presented for the same year for consistency. Table 2 provides water use definitions adapted from Templin et al. (1980) and information supplied by the states. These definitions were used for reported and unreported uses as indicated in the table. Water use for unconventional oil and gas was also considered, but no instances of that use were identified.

2.1 | Reported water uses

Reported water uses are disclosed to the state either voluntarily or because they are above state reporting thresholds and therefore require a withdrawal permit and reporting of the actual amount extracted. While each jurisdiction has its own set of water use categories and definitions, they generally fall under the 11 different use types listed in Table 2. Water use data are reported to the appropriate state agency and can be used for various research endeavors. Several states including Pennsylvania, Virginia, and West Virginia use the reported water use data to summarize available water resources and their associated use. This information is made available for public access (Table 3).

A challenge to designing and managing water use databases in an interstate basin such as the Potomac is the need to standardize data from multiple states and agencies. A previous ICPRB effort endeavored to create such a database for reported water withdrawals and associated consumptive uses for the non-tidal portion of the Potomac basin monthly from 1985 to 2012 (Ducnuigeen et al., 2015). The non-tidal portion of the Potomac basin includes all portions of the basin that drain into the Potomac River above or at the Fall Line near Little Falls (Figure 1). Both the previous and current efforts to compile the reported water withdrawals in the basin assume that water use reported in each sector is ultimately used in that sector. This is often referred to as the “end use.” There may be instances where water reported as public water supply is used for another sector, that is, a thermoelectric power plant that uses a public water supply as its source. For simplicity and consistency, these uses are maintained in the sector as they were reported to their state agency.

TABLE 2 Water use definitions by sector.

Sector	Use definition
Agriculture[u,r]	Irrigation water uses are water applied to crops or nursery plants that are grown for human or animal consumption or used for germination, chemical application, and harvesting. Reported irrigation also includes water used for dust suppression and irrigation of public lawns, parks, and golf courses
	Livestock water uses are water used to raise and maintain livestock and for other non-irrigation farm needs. Livestock include cattle, sheep, goats, hogs, poultry, and horses as well as other commercially raised animals
Aquaculture[u,r]	Water used to raise and cultivate aquatic animals and plants for food, recreation, conservation, enhancement, and restoration purposes
Commercial[r]	Water used for sanitation, maintenance, and aesthetic purposes by commercial, institutional, and recreational facilities that exchange, buy, or sell commodities or provide services, amusement, or relaxation. Examples include office buildings, retail stores, and other commercial facilities, government, military and educational institutions, state parks, golf courses, amusement parks, campgrounds, and sport, yacht, and country clubs
Hydroelectric[r]	Water used to generate electrical power where water is the motive force. In general, there is little or no consumptive use in the generation process (i.e., water flowing out of a dam to turn a turbine)
Industrial[r]	Water used for manufacturing or processing goods; washing, diluting, cooling, or transporting products; incorporating water into products; and sanitation needs within the manufacturing facility. This use category does not include mining, extraction of crude petroleum and gases, nor power generation because these are included in other categories
Mining[u,r]	Water used for extracting and on-site processing of coal, ores, nonmetallic minerals, and sand and gravel. The water is primarily used for quarrying, extracting, and milling but also indirectly for dust abatement, or may be lost by evaporation or during dewatering
Other[r]	Any water used for which a specific purpose could not be identified
Public water supply[r]	Water used by a municipality or a private water company to supply residences, commercial operations, and industries
Self-supplied domestic[u,r]	Water used and withdrawn directly by domestic users, often from a well. The water is used for domestic indoor household purposes (drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, etc.) and outdoor purposes (e.g., watering lawns and gardens)
Thermoelectric[u,r]	Water used to generate electricity with steam-driven turbine generators

Note: [r]Reported water use; [u]Unreported water use.

To further understand the reported water withdrawals within the entire Potomac basin the initial Withdrawal and Consumptive Use (WCU) database was updated to include withdrawals in the tidal portion of the basin and more recent data. These updates occurred through the collection of reported withdrawal data from the basin jurisdictions and resulted in an updated database that includes water withdrawal data for all 11 HUC8 watersheds in the Potomac basin from 2003 to 2019. Additional data from 1985 to 2003 is included for the non-tidal portion of the basin. Updates made to the WCU database include data available at the initiation of this project. Changes to state-reported withdrawal data may have occurred since that time. These are not reflected here but will be included in future modifications to and analyses using the WCU database.

To produce tables that contain withdrawal data from all Potomac basin jurisdictions, the WCU database required establishing a universal structure to which the state datasets could all be formatted. The challenge in developing this universal structure was ensuring that all information provided by each jurisdiction was included in the resulting format while still ensuring that attributes that may have a different name but represent the same information are combined into one column. Site descriptions include owner information, withdrawal use sector, HUC8 code, and other information about the withdrawal site.

To understand reported water withdrawals in the Potomac basin for each use sector by HUC8, summary statistics were performed to provide an overview of the reported withdrawals. As the unreported water withdrawals were largely estimated for the year 2017, the summarization of the reported withdrawals was performed for 2017 as well. This allows for a direct comparison of the reported and unreported water withdrawals by HUC8 watershed and use type.

2.2 | Unreported uses

Generally, there are water use categories that are not required to report withdrawals or for which withdrawal rates can be below reporting thresholds. These are aquaculture, irrigation, livestock, mining, self-supplied domestic, and thermoelectric. As such, these are considered unreported and were estimated as part of this effort. To estimate use amounts for these categories, a water use rate and spatial extent of the use were needed. Use rates were estimated by gathering available information from both peer- and non-peer-reviewed research conducted inside and/or outside of the basin. The spatial extent of each withdrawal type can be deduced from geospatial land use data, for example. Methods and data sources for making these estimates were developed from sources documented in Table 4.

TABLE 3 Publicly available state-reported water use data.

Jurisdiction/agency	Reporting timeline	Latest year available	Report type
District of Columbia	No reported withdrawals		
Maryland	No state-level report is available online		
PA Dept. of Environmental Protection	Annual	2021	Water Use Summary, Water Use Report by Facility, Water Use Report by Water Supplier
VA Dept. of Environmental Quality	Annual	2021	Annual Water Resources Report
WV Dept. of Environmental Protection	Annual	2021	Annual Water Resources Report

TABLE 4 Data sources and references for methods used to estimate unreported water uses.

Sector	Data sources	Method sources
Agriculture	2017 Census of Agriculture data (USDA NASS, 2019)	Irrigation estimates (Dickens et al., 2011) Livestock estimates (Lovelace, 2009)
Aquaculture	State water use databases, Fish and Boat Commissions, and Aquatic Network (Aquanet, 2019)	Active aquaculture operations are not listed in state permitted use databases; therefore, a default value of 10,000 gallons per day (GPD) per withdrawal was used
Mining	State mining data source, and State permitted water use databases	Active mines are not listed in state permitted use databases; therefore, a default value of 10,000 GPD per withdrawal was used
Self-Supplied Domestic	U.S. Census Bureau (2018); Counties and municipalities in VA (U.S. Census Bureau, 2018); and Maryland Department of Planning	(Kenny & Juracek, 2012; Moltz & Palmer, 2012; Stuckey, 2008)
Thermoelectric	U.S. Energy Information Administration (EIA, 2019a, 2019b); USGS water-use compilation data (Maupin et al., 2014); and USGS estimated data (Harris & Diehl, 2017)	(Diehl & Harris, 2014; Harris & Diehl, 2017)

2.2.1 | Agriculture

Agriculture is an integral part of the economy in the Potomac basin. However, agricultural water use in the basin is largely unreported. Those reported are mostly water used for dust suppression, lawns, parks, and golf courses. In this study, unreported water use was categorized as either water used for irrigation or for livestock. Unreported irrigation water use includes water applied to orchards, nurseries and crops grown for human or animal consumption. Unreported livestock water use includes water used to raise and maintain livestock such as cattle, sheep, goats, hogs, poultry, and horses. The methods used to estimate irrigation and livestock water uses are described in subsequent subsections.

2.2.2 | Irrigation

Most irrigation withdrawals in the U.S. are not metered, nor are they often required to be reported to state agencies especially if they are under 10,000 GPD (Turner et al., 2011). The USGS (Dickens et al., 2011) outlines sources of data used to estimate irrigation withdrawals and compares data and methods between state-level estimates and those made for the 2005 water-use report (Kenny et al., 2009). The report presents a standard method for estimating irrigation use (1) and documenting data sources. The water withdrawal estimate for irrigation is typically based on a water application rate, consumptive use, and conveyance-loss estimates. However, the application rates do not reflect the total amount of water withdrawn for irrigation. The total amount "can be affected by factors such as crop type, climate, method of irrigation, irrigation-system efficiencies, soil conditions, and availability of water" (Dickens et al., 2011).

To estimate the total withdrawal, USGS often accounts for all these factors in a single water-use coefficient that includes consumptive use and conveyance loss. The USGS defines conveyance loss as "water lost while in transport to irrigation systems" and irrigation-system efficiencies as "the fraction of applied water that is not consumed by the crop" (Dickens et al., 2011). In this study, estimated irrigation water use in each of Potomac basin's 11 sub-watersheds was determined using locally derived water use factors and irrigated acres of cropland obtained from the 2017 Census of Agriculture data.

Irrigation withdrawal for crops may be estimated using the following indirect irrigation withdrawal estimation method (Tadayon, 2005):

$$W = \frac{A \times C}{L}, \tag{1}$$

where, W is irrigation withdrawals for a crop (acre-feet), A is irrigated acreage of each crop during the growing season (acres), C is the consumptive-water requirement for each individual crop (feet), and L is all potential water loss (decimal fraction).

For the purposes of this effort, Equation (1) was modified: The consumptive-water requirement and potential water loss parameters were replaced with a water-use factor, Equation (2). The water-use factors were evaluated based on estimates of unreported water use for Virginia and Pennsylvania. There were no available water-use factors for Maryland and West Virginia; therefore, based on physiographic properties in the region, values for Virginia were assumed for both Maryland and West Virginia. Irrigation water use is calculated using water-use factors of 1450 GPD/acre (Maryland, Virginia, and West Virginia) and 1350 GPD/acre (Pennsylvania) and an irrigated acreage estimate from the Census of Agriculture data (USDA NASS, 2019).

$$W_t = \frac{\sum (A_i \times F_i)}{1{,}000{,}000}, \tag{2}$$

where, W_t is total irrigation withdrawal (MGD), A_i is irrigated acreage per county (acres), and F_i is average water-use factor (GPD/acre).

2.2.3 | Livestock

The method used to estimate unreported livestock water use from surface- and ground-water sources was based on the methods described in Lovelace (2009). The basic method is to estimate the number of head of livestock by animal type and multiply it by a water-use coefficient specific to that animal type, Equation (3). Lovelace (2009) defines the water use category to include "groundwater and surface water associated with livestock watering, feedlots, dairy operations, and other on-farm needs. The water may be used for drinking, cooling, sanitation, waste disposal, and other needs related to the animals. Categories of livestock may include dairy cattle, beef and other cattle, hogs and pigs, laying hens, broilers and other chickens, turkeys, sheep and lambs, all goats, and horses." The 2017 Census of Agriculture data (USDA NASS, 2019) was used to estimate livestock populations across the Potomac basin. Data that were not reported in the 2017 Census of Agriculture report were estimated from prior reports.

Water-use coefficients were obtained from Lovelace (2009) and are based on estimates from county extension service agents, local livestock experts, and various livestock management publication. Table 5 displays the range of coefficients for each animal type. In cases where state-specific values were not available, the median value was used.

The equation used to estimate livestock water withdrawals in the Potomac basin is as follows:

$$W_t = \frac{\sum \left(\left(\mathrm{DC}_i \times \mathrm{DC}_c \right) + \left(\mathrm{BC}_i \times \mathrm{BC}_c \right) + \left(P_i \times P_c \right) + \left(H_i \times H_c \right) + \left(L_i \times L_c \right) + \left(B_i \times B_c \right) + \left(S_i \times S_c \right) \right)}{1{,}000{,}000}, \tag{3}$$

where, W_t=total water withdrawals, in million GPD, DC=number of dairy cows, BC=number of beef and other cattle, P=number of hogs and pigs, H=number of horses, L=number of laying hens, B=number of broilers and other chickens, S=number of sheep and lambs, i=county, and c=coefficient for each animal type, in GPD.

TABLE 5 Water-use coefficients for livestock (reprinted from Lovelace, 2009).

	Water-use coefficients (gallons per animal per day)				
Animal type	Minimum	25th percentile	Median	75th percentile	Maximum
Dairy cows	18.00	20.00	35.00	35.00	65.00
Beef and other cattle, including calves	6.60	10.00	12.00	12.00	16.00
Hogs and pigs	2.00	2.60	3.50	4.50	8.10
Laying hens	0.03	0.05	0.06	0.09	0.12
Broilers and other chickens	0.02	0.04	0.06	0.07	0.10
Turkeys	0.05	0.08	0.10	0.12	0.22
Sheep and lambs	0.70	1.50	2.00	2.00	3.30
Goats	1.00	2.00	2.00	2.00	4.00
Horses	8.50	12.00	12.00	12.00	15.00

To determine unreported water use, the total amount of livestock water use reported by each county was subtracted from the estimated water withdrawal derived from the following equation:

$$\text{Unreported water use} = \text{estimated water withdrawal} - \text{reported water use}. \quad (4)$$

2.2.4 | Aquaculture

Aquaculture water use is associated with the cultivation of aquatic animals and plants for food, recreation, conservation, enhancement, and restoration purposes. Aquaculture production occurs mostly in ponds (either open or closed) or flow-through raceways but also in closed recirculating tanks, cages, and net pens, as well as in egg incubators by both commercial and noncommercial operations (Lovelace, 2009). Much of the water used for flow-through raceways is returned to the source and is available downstream. Likewise, cage and net pen operations use very little water as it simply passes through these production units. Most water withdrawn or diverted for aquaculture production is used to maintain water levels as water may be lost due to seepage or evaporation, and to maintain water quality but also for oxygenation, temperature control, and flushing (Lovelace, 2009). Some water consumption also occurs when biomass is harvested as the moisture content of aquatic organisms is 75% or more.

Water withdrawals for aquaculture are often self-supplied and typically account for only a small percentage of total water withdrawals. For example, (Dieter et al., 2018) state that aquaculture withdrawals were about 4% of the total water usage, excluding thermoelectric power, in the U.S. in 2015. During that year, surface water was the primary water source for the aquaculture sector in Virginia and West Virginia at almost 100 and 80%, respectively, but was used to a lesser extent in Maryland (26%) and Pennsylvania (49%) (Dieter et al., 2018).

Lovelace (2009) describes a method for estimating water withdrawal using water-use coefficients, water replacement rates, number of ponds or raceways, raceway flow rates, pond acreage, surface and groundwater withdrawals, weight of the organisms, and other factors. Although the USDA National Agricultural Statistics Service (NASS) provides much of the information required to estimate water use for commercial operations, which likely are reporting their water usage, these data were not readily available for noncommercial operations. In addition, Lovelace (2009) did not provide water replacement rates "…to avoid potential disclosure of confidential information…" Therefore, a different method had to be used to estimate potentially unreported water withdrawals.

Data sources including MDE's permitted user databases; Pennsylvania's Water Source Registration Report Viewer (PA WSRRV, 2019), Permitted Facilities Report Viewer (PA PFRV, 2019), and Fish and Boat Commission (PFBC, 2019); Virginia's surface water and groundwater permits (VA DEQ, 2019) and West Virginia's Large Quantity User (LQU) dataset, were queried to produce a list of permitted aquaculture operations.

Next, various online sources were assessed to locate aquaculture operation not listed in the datasets provided by the states, including state and commercial fish hatcheries listings as well as listings on the Aquatic Network directory (Aquanet, 2019). The locations of these operations were verified by using GIS when coordinates were known or Google Earth when only the address was provided. Unreported operations received a default withdrawal value of 10,000 GPD. Although withdrawal amounts could range from 0 to 10,000 GPD, this default amount per withdrawal was chosen because all Potomac basin states require users withdrawing more than 10,000 GPD to report the withdrawal.

2.2.5 | Mining

Mining operations withdraw surface water and/or groundwater for extraction and on-site processing of coal, ores, nonmetallic minerals, and sand and gravel. Water is primarily used for quarrying, extracting, and milling but may also be used for dust abatement or be lost through evaporation or dewatering. Water may be reused at the mine site or be discharged.

Lovelace (2009) used production data and water-use coefficients to estimate withdrawals for fuel mining (e.g., coal, natural gas, petroleum) and nonfuel-mining (i.e., metallic and nonmetallic minerals); however, the coefficients provided in the report varied greatly. For example, national values ranged from 140 to 1567 gallons per short ton of crude ore produced (gal/sh tn) in the case of metal mining, from 30 to 997 gal/sh tn for nonmetallic mineral mining, and from 50 to 59 gal/sh tn for coal mining (US Office of Management and Budget, 1987). Furthermore, Templin et al. (1980) states in the National Handbook of Recommended Methods for Water Data Acquisition that using water-use coefficients to estimate mining water withdrawals must be done with care because mining operations are influenced by local conditions, and thus coefficients may not be readily transferable between mine locations. Given these uncertainties, water-use coefficients were not used. Instead, a default withdrawal value for each mine in the basin was used as described below.

The first step in estimating unreported water use by the mining sector was to generate a list of active mines from state water use websites. This list was compared to the list of permitted water users provided by the state agencies. Any active mines not reporting to the states were assumed to be withdrawing water below the reporting threshold. It should be noted that only mining permits rather than individual withdrawal points (e.g., wells, surface water intakes, ponds) were counted. Mine locations were verified by either using a GIS when coordinates were provided or Google Earth when only addresses were given.

Each permit was assigned a withdrawal value of 10,000 GPD. Although withdrawal amounts could range from 0 to 10,000 GPD, a default value of 10,000 GPD for each withdrawal was chosen because all Potomac basin states require users withdrawing more than 10,000 GPD from surface water and/or groundwater sources to report the withdrawal. Additional details are provided for each state below.

The Maryland Department of the Environment (MDE) provided a dataset of all permitted water users, users not required to report water use quantities, and actual water usage as of 2018. All active mines that did not report water usage were used in the unreported use estimation.

To investigate whether all mining operations were reporting all water uses, the Pennsylvania Department of Environmental Protection (PA DEP) sent a questionnaire to mining operators in 2018 to locate potential unreported or under-reported sites. Information from the resulting dataset was compared to a list of mines that were active in 2018, which was compiled from several sources including:

- Pennsylvania's Water Source Registration Report Viewer (PA WSRRV, 2019),
- Pennsylvania's Permitted Facilities Report Viewer (PA PFRV, 2019),
- Pennsylvania's Coal and Industrial Minerals Mining Activities website (PA CIMMA, 2019), and
- eMapPA (2019) using the layer *Regulated Facilities and Related Information/Mining*.

It was assumed that active mines that were not reporting either did not withdraw water or withdrew amounts below Pennsylvania's reporting requirement. These mines were assigned the default value of 10,000 GPD.

The Virginia Department of Environmental Quality Water Withdrawal Permitting and Compliance Program (VA DEQ WWPCP) is responsible for both groundwater and surface water withdrawal permitting and reporting and maintains lists of current permits on their website (VA DEQ, 2019). A search of their data revealed no active registered mines within the Potomac basin.

To further investigate mine locations in Virginia, active mineral mining permits, annual production data, and an interactive GIS mining map from Virginia's Department of Energy Mineral Mining Division (VA DMM, 2019) as well as active coal mine data (VA DMINQUIRY, 2019) were queried to create a list of active mines located within the Potomac basin. However, since none of these sites were recorded by VA DEQ WWPCP in 2018, it is likely that they either did not withdraw water or withdrew amounts below Virginia's reporting requirement. Consequently, when the tonnage produced by these mines was above zero in the DMM data, they were deemed nonreporting, and each permit was allocated the default value of 10,000 GPD.

The West Virginia Department of Environmental Protection (WV DEP) provided a LQU dataset that included reported water usage and location data as of 2018. This dataset was queried for active permitted mines within the Potomac basin. Because the dataset only tracked LQUs, other sources were consulted to locate potential unreported mining activities, including the Mining Data Explorer (WV DEP, 2019a), the Coal and Quarry NPDES Permit Search tool (WV DEP, 2019b), and data from the West Virginia Office of Miners (WV OM, 2019). The result of these queries was compared to West Virginia's LQU dataset. Any mines not found in the LQU dataset were considered to be unreported water users and were assigned the default value of 10,000 GPD.

2.2.6 | Self-supplied domestic

Self-supplied domestic withdrawals in the U.S. are rarely metered or reported (Dieter et al., 2018). The accepted estimation method is to multiply an estimate of the population not served by public water supply by a per capita water use coefficient (Dieter et al., 2018; Kenny & Juracek, 2012; Moltz & Palmer, 2012). To apply this method in the Potomac basin, areas outside of current public water supply service areas were assumed to be self-supplied domestic.

To estimate the number of people in these self-supplied domestic areas, the geographic areas outside of public water supply service areas were identified using the following data sources: 2010 U.S. Census block population data and a GIS layer of the census blocks (U.S. Census Bureau, 2018), boundaries of Pennsylvania public supply service areas, Maryland's generalized sewer area (as a surrogate for the public supply service area), and Virginia's sewer service areas and public water service areas (obtained from individual counties and municipalities in Virginia).

The populations of the self-supplied domestic areas (census blocks in the Potomac basin outside of public water supply service areas) were estimated using the 2010 census data. For census blocks where the watershed boundary or the service area crossed the block boundary, the population was adjusted by area weighting the population of the census block (Moltz & Palmer, 2012). Next, a reasonable water use coefficient was identified. In the literature, self-supplied domestic water use rates in the U.S. range from 36 gallons per capita per day (GPCD) in Connecticut to 186 GPCD in Nevada in 2015, with a national average of 77 GPCD (Dieter et al., 2018). In the USGS's study, self-supplied domestic use for Maryland, Virginia, and West Virginia was 80 GPCD and 60 GPCD for Pennsylvania in 2015. Since it covers the majority of Potomac basin area, 80 GPCD was used as a water use coefficient in this study. The population estimates described above were multiplied by the 80 GPCD coefficient to estimate self-supplied domestic water use for census blocks in the basin. The block-level data were aggregated to the county/municipality and HUC8 levels.

2.2.7 | Thermoelectric

Thermoelectric power was one of the largest users of water in the U.S. in 2015 (Dieter et al., 2018). Water is used for generating electricity with steam-driven turbine generators in thermoelectric power plants. Nationwide, sources of water for thermoelectric power plant cooling include fresh and saline water from both surface water and groundwater sources, with reclaimed wastewater as a supplemental source (USGS, 2020)

A list of thermoelectric power plants in the basin and a water use coefficient were used to estimate the water use in the thermoelectric sector. There are three federal datasets for thermoelectric water withdrawals in the U.S. including U.S. Energy Information Administration (EIA) data (EIA, 2019a, 2019b), USGS water-use compilation data (Maupin et al., 2014), and USGS estimated data (Harris & Diehl, 2017). The datasets have different approaches to estimate both withdrawals and the number of power plants.

The EIA publishes thermoelectric water use data annually while the USGS does not publish either the compilation data or estimated data frequently (Harris & Diehl, 2017). For this study, a list of power plants and their location in the basin was downloaded from the EIA database (EIA, 2019a). This list was compared to the list from state reported water use databases. Those plants not included in the reported water use databases were considered unreported for the purposes of this study. No unreported thermoelectric water uses were identified in the Potomac basin. As a result, unreported thermoelectric water uses in the Potomac basin were assumed to be zero GPD.

3 | RESULTS

Water withdrawals reported to Potomac basin jurisdictions for 2017 equate to approximately 4092.59 million GPD (MGD, 1 MGD is equivalent to approximately 3785 cubic meters per day) (Table 6). Overall, hydroelectric and thermoelectric represent more than three-quarters (77.7%) of the reported water withdrawn (Figure 2). The remaining reported water withdrawals are mainly associated with public water supply (16.3%) (Figure 2). Commercial, irrigation, livestock, aquaculture, and self-supplied domestic water use each represent less than 1% of total reported water withdrawals.

Unreported water uses in 2017 is approximately 180.60 MGD, with self-supplied domestic representing almost half (47.6%) of the total unreported water uses (Table 6). The next largest unreported water uses are irrigation and livestock (23.3% and 28.5%, respectively) (Figure 3). Mining and aquaculture combined represent only 0.6% of unreported water uses. Lastly, there were no identified unreported water withdrawals in the thermoelectric sector.

Estimated water usage by sector, both reported and unreported, and by HUC8 watershed are described in more detail in the following sections. A supplemental table provides results at a higher geographic resolution, by HUC8 watershed and locality (ICPRB, 2022).

TABLE 6 Reported and unreported water use by HUC8 in the Potomac basin in million GPD (MGD).

HUC8 name	Reported	Unreported	Total
South Branch Potomac	13.15	3.09	16.24
North Branch Potomac	1052.45	8.58	1061.03
Cacapon-Town	0.74	5.45	6.19
Conococheague-Opequon	690.00	34.61	724.61
South Fork Shenandoah	39.17	33.64	72.81
North Fork Shenandoah	16.20	17.39	33.59
Shenandoah	503.59	8.13	511.72
Middle Potomac-Catoctin	736.46	17.80	754.26
Monocacy	34.15	15.15	49.30
Middle Potomac-Anacostia-Occoquan	87.36	15.23	102.59
Lower Potomac	919.31	21.53	940.84
Total	4092.58	180.60	4273.18

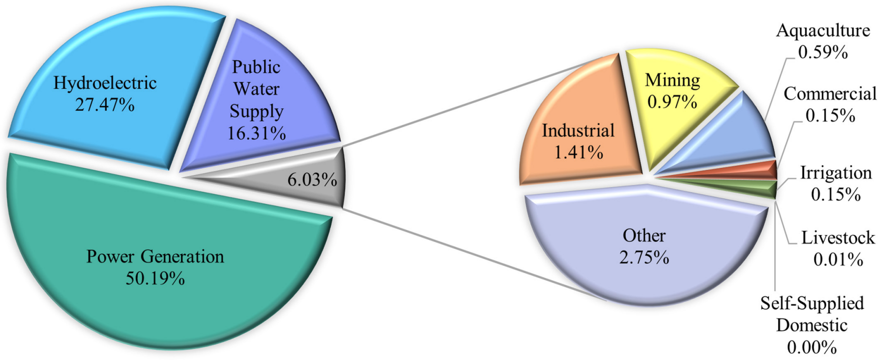

FIGURE 2 Percent of reported water withdrawals by sector in the Potomac basin.

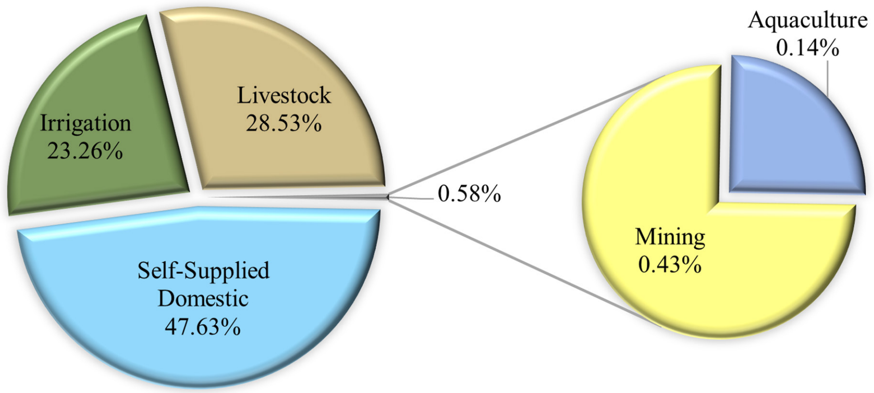

FIGURE 3 Percent of estimated unreported water use by sector in the Potomac basin.

3.1 | Agriculture

Reported water withdrawals for agriculture, both irrigation and livestock combined, were 6.55 MGD or 0.16% of the total reported water withdrawals in the basin. Most of the reported agriculture water withdrawals are for irrigation purposes as opposed to livestock with an estimated 6.03 MGD and 0.52 MGD, respectively (Table 7).

The reported irrigation water withdrawals are largely from the South Fork Shenandoah, Middle Potomac-Catoctin, and Middle Potomac-Anacostia-Occoquan watersheds which account for 4.06 MGD (67.3%) of all reported irrigation withdrawals (Table 7). All three of these watersheds have reported withdrawals of over 1 MGD. The remaining 32.7% of reported irrigation withdrawals originate from six of the eight remaining HUC8 watersheds.

While large agricultural producers (those withdrawing 10,000 GPD or more) are required to report withdrawals to state agencies, those that withdraw less are not required to do so. Unreported water use for both irrigation and livestock were computed at the county level then aggregated to the watershed level. In general, livestock production utilizes more water in the Potomac basin than irrigation.

The total unreported livestock water use is a little under 52 MGD which accounted for approximately 29% of total unreported water uses for all categories, excluding thermoelectric power. Three watersheds (Conococheague-Opequon, South Fork Shenandoah and North Fork Shenandoah) accounted for 65% of the total livestock unreported water use (Table 7). In comparison to the other 10 watersheds, livestock water use in the Middle Potomac-Catoctin is almost negligible (0.17 MGD), accounting for a mere 0.33% of total livestock unreported water use.

3.2 | Aquaculture

Nationwide, water usage by the aquaculture sector typically amounts to only a small percentage of total water withdrawals by all sectors. This is also true for the Potomac basin. The aquaculture sector accounts for 0.59% (24.24 MGD) of the total reported water withdrawals and mostly occur in the South Branch Potomac, Conococheague-Opequon, and Monocacy watersheds (Table 8). Unreported aquaculture withdrawals

TABLE 7 Reported and unreported irrigation and livestock withdrawals (MGD) by HUC8 in the Potomac basin.

HUC8 name	Irrigation			Livestock		
	Reported	Unreported	Total	Reported	Unreported	Total
South Branch Potomac	0	0.14	0.14	0	0.93	0.93
North Branch Potomac	0.11	1.19	1.3	0	3.05	3.05
Cacapon-Town	0	0.45	0.45	0	2.47	2.47
Conococheague-Opequon	0.38	5.11	5.49	0.04	12.02	12.06
South Fork Shenandoah	1.32	9.59	10.91	0.01	14.63	14.64
North Fork Shenandoah	0.15	5.3	5.45	0.2	6.89	7.09
Shenandoah	0.11	0.83	0.94	0.06	2.82	2.88
Middle Potomac-Catoctin	1.3	7.48	8.78	0.01	0.17	0.18
Monocacy	0.66	2.9	3.56	0.2	2.99	3.19
Middle Potomac-Anacostia-Occoquan	1.44	2.89	4.33	0	2.46	2.46
Lower Potomac	0.56	6.15	6.71	0	3.09	3.09
Total	6.03	42.03	48.06	0.52	51.52	52.04

TABLE 8 Reported and unreported aquaculture withdrawals (MGD) by HUC8 in the Potomac basin.

HUC8 name	Reported	Unreported	Total
South Branch Potomac	8.41	0.04	8.45
North Branch Potomac	0.30	0.01	0.31
Cacapon-Town	0.00	0.00	0.00
Conococheague-Opequon	9.32	0.04	9.36
South Fork Shenandoah	0.96	0.01	0.97
North Fork Shenandoah	0.73	0.03	0.76
Shenandoah	0.00	0.00	0.00
Middle Potomac-Catoctin	0.01	0.03	0.04
Monocacy	4.25	0.04	4.29
Middle Potomac-Anacostia-Occoquan	0.00	0.04	0.04
Lower Potomac	0.27	0.02	0.29
Total	24.24	0.26	24.50

account for only 0.14% (0.26 MGD) of the estimated total unreported water usage (Figure 3). Table 8 shows the estimated unreported withdrawals by the aquaculture sector by HUC8 watershed. No unreported withdrawls by aquaculture operations were found in the Cacapon-Town or Shenandoah watersheds. The remaining watersheds had between one and four operations each.

3.3 | Commercial

In the Potomac basin approximately 6.32 MGD, or 0.15% of total reported water withdrawals, are used for commercial purposes (Table 9). The majority of these withdrawals come from the Middle Potomac-Anacostia-Occoquan and the Lower Potomac watersheds, with withdrawals of 1.33 MGD and 1.42 MGD, respectively (Table 9). For the remaining watersheds, commercial use is less than 1 MG in each.

3.4 | Hydroelectric

In the Potomac basin all water used for hydroelectric purposes is reported to the states. Hydroelectric withdrawals are in the Conococheague-Opequon and Shenandoah watersheds. In these two watersheds, the hydroelectric sector amounts to 27.5% (1124.27 MGD) of the total reported withdrawals in the basin (Table 10) and are all associated with the Allegheny Energy Supply Company.

TABLE 9 Reported commercial water use (MGD) by HUC8 in the Potomac basin.

HUC8 name	Reported
South Branch Potomac	0.01
North Branch Potomac	0.07
Cacapon-Town	0.02
Conococheague-Opequon	0.92
South Fork Shenandoah	0.47
North Fork Shenandoah	0.34
Shenandoah	0.25
Middle Potomac-Catoctin	0.82
Monocacy	0.67
Middle Potomac-Anacostia-Occoquan	1.33
Lower Potomac	1.42
Total	6.32

TABLE 10 Reported water use for hydroelectric purposes (MGD) by HUC8 in the Potomac basin.

HUC8 name	Reported
South Branch Potomac	0
North Branch Potomac	0
Cacapon-Town	0
Conococheague-Opequon	625.46
South Fork Shenandoah	0
North Fork Shenandoah	0
Shenandoah	498.82
Middle Potomac-Catoctin	0
Monocacy	0
Middle Potomac-Anacostia-Occoquan	0
Lower Potomac	0
Total	1124.27

3.5 | Industrial

In the Potomac basin, industrial water withdrawals are all above the state-required reporting threshold and thus fully accounted for. They account for 11.7% (57.7 MGD) of the total reported water in the basin (Table 11). Over half of the industrial reported water withdrawals are in the North Branch Potomac watershed (Table 11). The largest user of water for industrial purposes in this watershed is the Verso Luke Paper Mill, which closed in 2019.

3.6 | Mining

Table 12 provides a summary of the estimated withdrawals by mining sector by HUC8 watershed. Mining accounts for about 0.97%, or 39.58 MGD, of the reported water uses in the Potomac basin (Figure 2). Of the reported water withdrawals for mining purposes, the largest withdrawals occur in the North Branch Potomac, Conococheague-Opequon, and Monocacy watersheds.

Unreported water use by the mining sector in the basin is 0.78 MGD, which represents only a small percentage (0.43%) of the estimated total unreported water use by all sectors (Figure 3). Most unreported water use by the mining sector occurs in the Conococheague-Opequon watershed at 0.23 MGD, followed by the Lower Potomac watershed at 0.12 MGD (Table 12). These two watersheds account for almost 45% of the estimated unreported water withdrawal by the mining sector.

TABLE 11 Reported industrial water use (MGD) by HUC8 in the Potomac basin.

HUC8 name	Reported
South Branch Potomac	0
North Branch Potomac	35.75
Cacapon-Town	0
Conococheague-Opequon	0.13
South Fork Shenandoah	10.68
North Fork Shenandoah	3.59
Shenandoah	0.07
Middle Potomac-Catoctin	0.77
Monocacy	5.51
Middle Potomac-Anacostia-Occoquan	0.19
Lower Potomac	1.01
Total	57.70

TABLE 12 Reported and unreported mining withdrawals (MGD) by HUC8 in the Potomac basin.

HUC8 name	Reported	Unreported	Total
South Branch Potomac	0.10	0.04	0.14
North Branch Potomac	8.18	0.08	8.26
Cacapon-Town	0.00	0.00	0.00
Conococheague-Opequon	17.81	0.23	18.04
South Fork Shenandoah	0.00	0.09	0.09
North Fork Shenandoah	0.00	0.06	0.06
Shenandoah	0.00	0.01	0.01
Middle Potomac-Catoctin	0.14	0.04	0.18
Monocacy	10.67	0.04	10.71
Middle Potomac-Anacostia-Occoquan	0.77	0.07	0.84
Lower Potomac	1.92	0.12	2.04
Total	39.58	0.78	40.36

3.7 | Public water supply

Public water supply withdrawals are required by the relevant state agencies to be reported. Across the 11 watersheds, approximately 16.3% of the reported withdrawals are for public water supply. Of the 667.36 MGD of reported public water supply withdrawals, 69.3% are located within the Middle Potomac-Catoctin watershed (Table 13). The majority of these are associated with the major water suppliers for the Washington, D.C., metropolitan area—including the Washington Aqueduct, Fairfax County Water Authority, and the Washington Suburban Sanitary Commission.

3.8 | Self-supplied domestic

Due to the nature of self-supplied domestic withdrawals, they often do not require reporting to state agencies and thus account for only a small portion of the reported withdrawals. For all 11 HUC8 watersheds in the basin, reported self-supplied domestic water withdrawals equated to about 0.17 MGD, or <0.01% of the total reported withdrawals (Table 14). These withdrawals originate from only three HUC8 watersheds—Conococheague-Opequon, Monocacy, and Lower Potomac (Table 14).

The total unreported self-supplied domestic withdrawal was approximately 86 MGD which accounted for 47.6% of total unreported withdrawals in the Potomac basin (Figure 3). This is the largest unreported water use sector in the Potomac basin.

TABLE 13 Reported public water supply water use (MGD) by HUC8 in the Potomac basin.

HUC8 name	Reported
South Branch Potomac	4.63
North Branch Potomac	10.24
Cacapon-Town	0.72
Conococheague-Opequon	35.92
South Fork Shenandoah	25.74
North Fork Shenandoah	11.19
Shenandoah	4.29
Middle Potomac-Catoctin	462.68
Monocacy	11.98
Middle Potomac-Anacostia-Occoquan	82.96
Lower Potomac	17.01
Total	667.35

TABLE 14 Reported and unreported self-supplied domestic withdrawals by HUC8 in the Potomac basin in MGD.

HUC8 name	Reported	Unreported	Total
South Branch Potomac	0.00	1.94	1.94
North Branch Potomac	0.00	4.25	4.25
Cacapon-Town	0.00	2.53	2.53
Conococheague-Opequon	0.02	17.21	17.23
South Fork Shenandoah	0.00	9.32	9.32
North Fork Shenandoah	0.00	5.11	5.11
Shenandoah	0.00	4.47	4.47
Middle Potomac-Catoctin	0.00	10.08	10.08
Monocacy	0.12	9.18	9.30
Middle Potomac-Anacostia-Occoquan	0.00	9.77	9.77
Lower Potomac	0.02	12.15	12.17
Total	0.16	86.01	86.18

3.9 | Thermoelectric

Thermoelectric water use accounts for approximately half of all reported water withdrawals in the Potomac basin at 2054.04 MGD (Table 15). Overall, the withdrawals for thermoelectric purposes can be attributed to only 168 sites across six different companies. The majority of these withdrawals originate in the North Branch Potomac and Lower Potomac watersheds. These watersheds also have the largest total reported water withdrawals across all sectors. Covering portions of Pennsylvania, Maryland, and West Virginia, the largest quantity of reported water withdrawals in the North Branch Potomac watershed are associated with the Mount Storm Power Station. Specifically, the North Branch Potomac watershed has reported water withdrawals totaling 1052.45 MGD with 997.8 MGD (94.8%) coming from the thermoelectric power sector (Table 15).

The Lower Potomac watershed is also dominated by the thermoelectric sector. Total withdrawals in the Lower Potomac watershed are 919.31 MGD with 784.94 MGD (85.4%) originating from thermoelectric power use (Table 15). These withdrawals are largely attributed to the NRG Morgantown Generating Station.

Unlike reported water use, there were no unreported thermoelectric water withdrawals identified in the Potomac basin as part of this effort.

3.10 | Other

In the reported water use analysis, some of the specific uses could not be categorized by sector or were extremely specific and did not fit into one of the other use categories. In these instances, the water use sector was identified as "other." Most of the reported water withdrawals

TABLE 15 Reported thermoelectric withdrawals in MGD.

HUC8 name	Reported
South Branch Potomac	0
North Branch Potomac	997.80
Cacapon-Town	0
Conococheague-Opequon	0
South Fork Shenandoah	0
North Fork Shenandoah	0
Shenandoah	0
Middle Potomac-Catoctin	270.75
Monocacy	0.09
Middle Potomac-Anacostia-Occoquan	0.46
Lower Potomac	784.94
Total	2054.04

in this category, 112.15 MGD, are associated with the Dominion Possum Point Power Plant located in the Lower Potomac watershed. The specific use(s) of these withdrawals could not be identified. The additional 0.22 MGD in this category are associated with contamination wells.

4 | DISCUSSION

With quantifications of reported and unreported water uses in hand by HUC8, estimates of total water use are now possible (Table 6) with 4273.18 MGD of water use identified in the Potomac basin. While 96% of that total is accounted for in the state reported data, unreported water use can account for a much larger portion of the overall water use budget, over 80% in the Cacapon-Town watershed (Figure 4). Specifically, there are two watersheds in the Potomac basin for which the unreported use is greater than the reported use: Cacapon-Town and North Fork Shenandoah. This finding of an unreported water use of 50% or more of the total withdrawal provides a critical piece of information for managing water use and availability. The South Fork Shenandoah's unreported water use is a similar percentage, at 46%. Unreported water use makes up a significant percentage in the Monocacy (30%) and South Branch Potomac (19%) watersheds as well.

This is particularly interesting as irrigation and livestock uses make up 23.26% and 28.53%, respectively, of the total unreported use in the basin. Consumptive use rates for these sectors can be between 76% and 93% depending on the specific use type and the month the water is used (Shaffer, 2009), meaning that a relatively large portion of a HUC8's water may be removed from the system at certain times of the year.

Figure 4 shows the percent of total water use that is unreported. Given that reported hydroelectric and thermoelectric dominate water use in several HUC8s (and make up nearly three quarters of total—reported and unreported—water use in the basin while being from only six thermoelectric and two hydroelectric companies), a map exploring the percent of total water use excluding reported hydroelectric and thermoelectric was also developed (Figure 5). These findings represent a new look at total water use in the Potomac basin, providing a clearer picture of needs than has been available to date.

This is the type of detailed information that is essential to water managers and those who rely on a predictable source of water. Specifically, in the Potomac basin the Washington, D.C., area is served by three large suppliers who rely year-round on the mostly free-flowing river. During drought periods their supplies are augmented by releases from upstream reservoirs. Their long-term plans and reliability studies for these hinges on water availability analyses that factor in upstream uses. The new estimates of unreported water use could bolster their understanding of water availability. Similarly, smaller municipalities in the Potomac basin are susceptible to droughts and the effects of climate change on water availability (Ahmed et al., 2020; Schultz et al., 2017). There are examples of small watersheds where demands are known to exceed supplies during times of low flow and instances of water needing to be trucked to small municipalities during times of drought.

These findings will be shared widely with Potomac basin stakeholders, including the Comprehensive Plan Advisory Committee, ICPRB Commissioners, and state water supply agencies. They can also be made available to local-level planners who may or may not be required to account for water availability when making development decisions. This study also serves as a resource for planners and managers more broadly—to understand that it is essential to include both large, reporting water withdrawals as well as the cumulative effects of smaller withdrawals in planning studies.

As the USGS highlights, "Water-use information is a critical component of water budgets, which are essential to surface-water and groundwater availability studies. This information is also essential to accurately understand how future water demands will be met while maintaining adequate water quality and quantities for human and ecosystem needs in the United States" (Dieter et al., 2018). Recognizing that it is critical

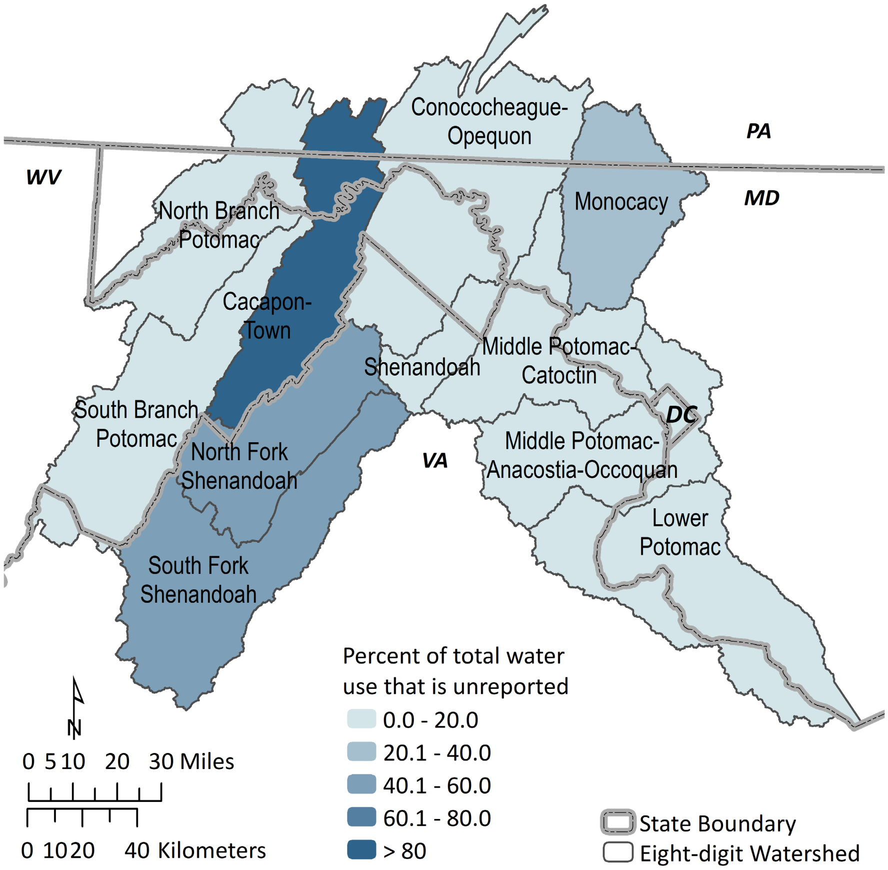

FIGURE 4 Percent of total water use that is unreported, by HUC8.

that water uses be reported as consistently as possible across jurisdictions, ICPRB is advocating for regular reporting in all Potomac basin states (Palmer & Moltz, 2013) and continues to encourage conversations on data consistency. It is the organization's intent to repeat this water-use analysis every 5 years. Thus, both providing up-to-date information for planning agencies and the opportunity to evaluate water-use trends at the HUC8 and basin scales.

5 | UNCERTAINTY

Studies of this magnitude contain uncertainties. However, these studies are important to inform and provide guidance for water resources management and water budget planning in river basins despite the uncertainties. This section highlights key challenges that were encountered and steps that were taken to address them, including assumptions that were made.

Uncertainty associated with the estimation of reported water withdrawals is largely related to the sheer quantity of data that are reported to each state in the Potomac basin. Changes in withdrawal location information, missing or incorrect location information, and changing site numbers for the same site were constant challenges. In addition, water use codes and definitions varied between the states, making it necessary to create overeaching definitions. State-to-state variations in water use data collection and analyses are also highlighted as potential sources of uncertainty in Ivahnenko et al. (2021). Even with these variations, Ivahnenko et al. (2021) produced valuable estimates of water withdrawals and use in the Upper Rio Grande basin. Furthermore, public water supply withdrawals can serve many end uses besides drinking water (e.g., fire prevention, commercial facilities, thermoelectric plants). Difficulties associated with identifying the end use of water withdrawals for public water supply uses are highlighted in Thompson and Pindar (2021) and VA DEQ (2022). For consistency, the originally designated withdrawal use sector was maintained in this study, just as was done in Thompson and Pindar (2021). No attempt was made to recategorize the sector based on the end use of the water.

Uncertainty associated with the estimation of unreported water use is related to data availability and inconsistencies between jurisdictions and localities. Examples include:

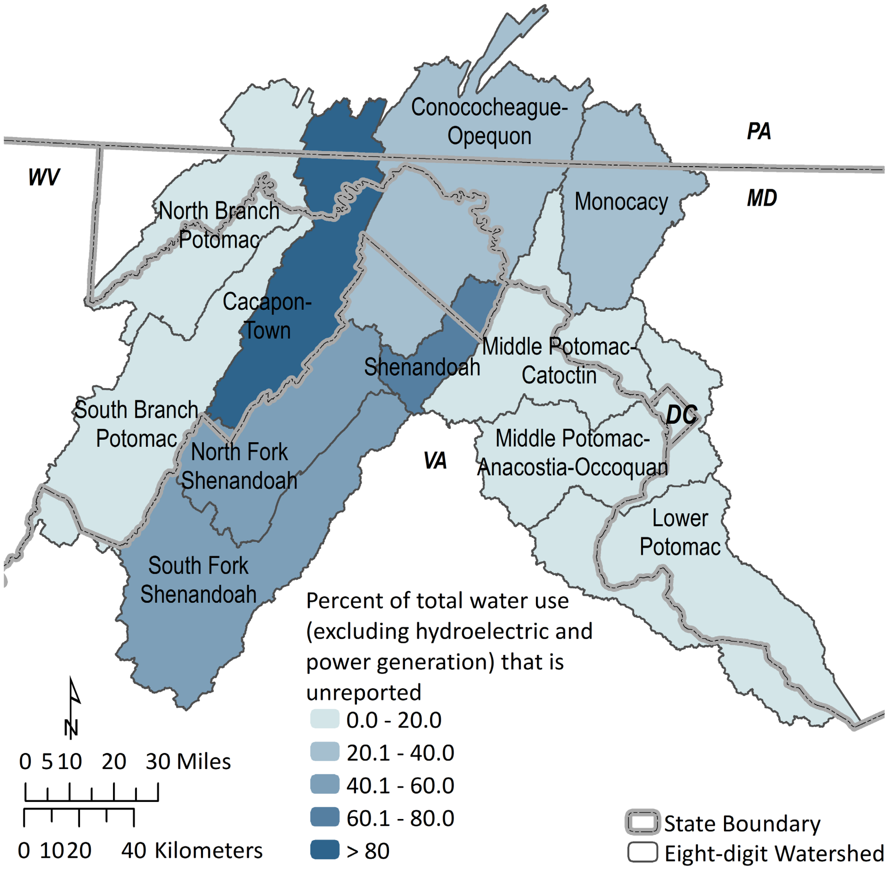

FIGURE 5 Percent of water use not including reported hydroelectric and reported thermoelectric that is unreported, by HUC8, since reported hydroelectric and thermoelectric dominate water use in some HUC8s.

- Data sources were sometimes for different water years, requiring interpolation or extrapolation to make datasets comparable. Stuckey (2008) also used data from similar years (i.e., the 2000 US Census and the 2002 Census of Agriculture) to compile a comprehensive study of unreported water uses.
- Use of generic per capita (human and animal) water use coefficients and irrigation rates. For example, when estimating unreported irrigation water use, water-use factors and irrigated acreages are two of the most important components. Dickens et al. (2011) documents the uncertainty associated with potential water loss, which is incorporated into the water-use factors used in this study, when estimating withdrawals for irrigation purposes. Counties in Maryland and West Virginia did not have county-specific water-use factors, and because the water-use factors are evaluated at the county scale, creative solutions were required for those counties. As a result, the Virginia and Pennsylvania water-use factors were used as surrogates.
- Estimates of irrigated acreages were limited to the 2017 Census of Agriculture. There was no way of assessing whether all irrigated acreages were reported. This source of uncertainty is further supported by Dickens et al. (2011) who highlights the differences in the estimated change in irrigated acres associated with different source data (i.e., USGS and USDA). Much of the information necessary to estimate water use by the mining and aquaculture sectors were not readily available, and therefore operations that were considered unreported received a default value of 10,000 GPD.

Quantitative estimates of uncertainty are a challenge for this type of analysis; however, they would be a valuable improvement for future iterations of this study in the Potomac basin.

6 | CONCLUSION

Historically, water-use analyses in the Potomac basin have focused solely on reported water uses. This has neglected a significant portion of water use in the basin: unreported uses. This new analysis shows that while individual unreported water uses are relatively small, they can collectively impact a water availability budget. This is especially true in watersheds where self-supplied domestic, irrigation, and livestock water uses are prevalent. In the case of irrigation and livestock, which have comparatively high consumptive use rates, this finding could inform the urgency with which land and water conservation measures are implemented.

Furthermore, this study shows that unreported use for an entire basin may be small, but when looked at the watershed level, unreported use can exceed reported use. For the entire Potomac basin unreported water use was only 4% of the total, but at the watershed level it was found that unreported water use in the Cacapon-Town and North Fork Shenandoah watersheds exceeded that of reported uses and is nearly equal in the South Fork Shenandoah watershed. Without this knowledge, decisions, such as the approval of a new withdrawal or withdrawal rates during a drought, solely based on reported water use dramatically underestimate total water use.

Including an estimate of unreported water uses provides a more complete understanding of total water use for the year 2017. Given that these are made up of largely agricultural uses with high consumptive use rates, this is an important piece of the water budget puzzle that needs to be accounted for when considering future water availability. Going forward, all water uses should be considered when assessing potential human impacts on aquatic habitats, human needs for water, and the exacerbating impacts of climate change.

AUTHOR CONTRIBUTIONS

Carlington W. Wallace: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing – original draft; writing – review and editing. **Heidi L. N. Moltz:** Conceptualization; data curation; funding acquisition; investigation; project administration; resources; supervision; writing – original draft; writing – review and editing. **Andrea Nagel:** Conceptualization; data curation; investigation; methodology; visualization; writing – original draft; writing – review and editing. **Stephanie Nummer:** Formal analysis; investigation; resources; validation; writing – review and editing. **Karin R. Bencala:** Conceptualization; project administration; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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