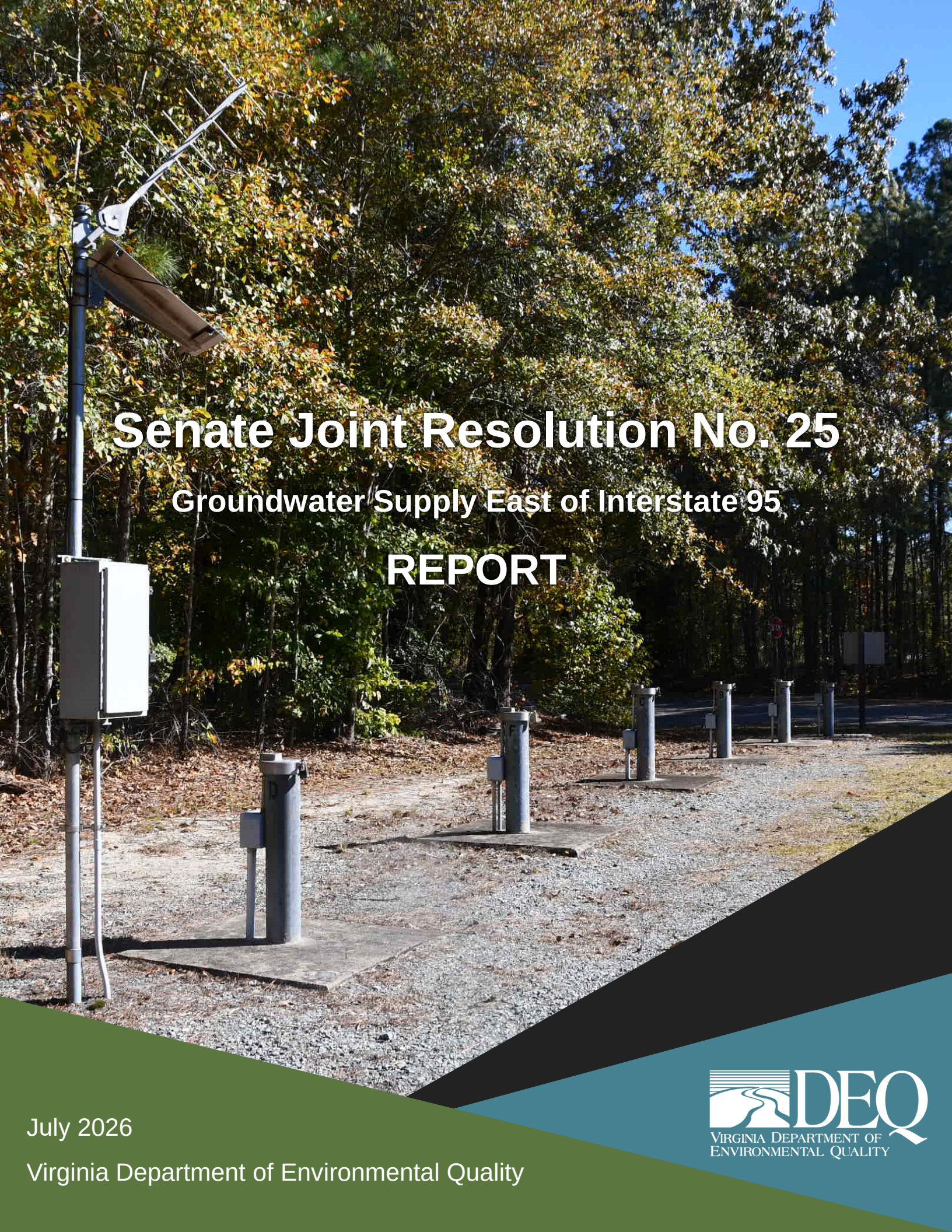




Senate Joint Resolution No. 25

Groundwater Supply East of Interstate 95

REPORT

July 2026

Virginia Department of Environmental Quality



Cover: Multi-well research station with real-time monitoring and telemetry equipment
in New Kent County, Virginia (State Observation Wells 233A–233F).
Photo by T. Scott Bruce, Virginia Department of Environmental Quality.

Groundwater Supply East of Interstate 95: Key Points

As directed by Senate Joint Resolution No. 25, the Virginia Department of Environmental Quality (DEQ) completed a study of the groundwater supply in the Commonwealth east of Interstate 95 (I-95). This area generally encompasses the Virginia Coastal Plain (VCP) aquifer system.

1. The confined Potomac aquifer is the largest and deepest in the VCP, accounting for 70% of total reported and estimated groundwater withdrawals in the Eastern Virginia Groundwater Management Area. The confined Yorktown-Eastover aquifer system accounts for 95% of total reported and estimated groundwater withdrawals in the Eastern Shore Groundwater Management Area. **Combining the two regulated areas, the major uses of groundwater are industrial (35% of total), private domestic (34%), and public water supply (26%).**
2. **The growing population of private domestic groundwater users in the VCP is projected to increase the total annual withdrawal rate by 200,000 to 300,000 gallons per day, on average, each year through 2050.** These lawful, unpermitted withdrawals are not reported to DEQ. Instead, they must be estimated from census and water-use data.
3. **Major withdrawals, especially at paper mills near Franklin and West Point, have caused inland groundwater levels to decline below sea level, altering the predevelopment flow pattern in the VCP.** Multiple lines of evidence show that groundwater now tends to flow inward from the margins toward the withdrawal centers and downward from higher to lower units in the VCP aquifer system.
4. These conditions cause land subsidence (sinking) and the potential for regional saltwater intrusion (saline water moving into freshwater aquifers). **Chloride concentrations in the aquifer system are increasing locally in some parts of Eastern Virginia and on the Eastern Shore.**
5. The Franklin Mill closed in 2010 and partially reopened in 2012, causing a temporary rebound of groundwater levels that spread outward. From 2014 to 2017, DEQ undertook a special groundwater-management initiative. Consequently, the Potomac aquifer's annual overall groundwater deficit was reduced to nearly zero for about a decade. **Regional groundwater levels rose and broadly stabilized until about 2021. Rising trends then stalled and began to reverse as the temporary rebound spread, diminished, and was consumed by ongoing withdrawals across the region, including at the Franklin Mill. Under current conditions, groundwater levels throughout the Potomac aquifer are expected to enter a period of decline in the next five to ten years.**
6. In the Potomac aquifer, hydraulic pressure effects travel tens of thousands of times faster than the typical flow of groundwater molecules through sediments. **Injections of water into the aquifer may yield a regional increase in groundwater levels with only local migration of the injected water molecules. However, regional water-level gains may dissipate rapidly when the injections cease.** This finding complicates the forecasting of groundwater levels that could result from aquifer replenishment, such as the Sustainable Water Initiative for Tomorrow (SWIFT).
7. **Under current conditions, the VCP aquifer system has limited capacity for significant new withdrawals.** The estimated capacity for new withdrawals varies by region, from a maximum of 360,000 gallons per day in the eastern Northern Neck to less than 30,000 gallons per day in some western regions near I-95. Only the upper end of this range would support a significant new withdrawal for industrial use.
8. **The Ground Water Management Act of 1992 has achieved mixed results.** The regulatory framework enabled the Commonwealth to stabilize groundwater-level gains that resulted from the unrelated closure of the Franklin Mill in 2010. However, groundwater supply east of I-95 is constrained, and current projections indicate declining availability in the near future.

Executive Summary

As directed by Senate Joint Resolution No. 25 (SJ 25), the Virginia Department of Environmental Quality (DEQ) has completed a study of the groundwater supply in the Commonwealth east of Interstate 95 (I-95), an area that generally coincides with the Virginia Coastal Plain (VCP). The accompanying report represents, to date, the most comprehensive effort to address the complex question of how much groundwater supply is available in this important region of the Commonwealth. Key figures are presented in this Executive Summary, and many additional illustrations and data tables appear in the full report. The report begins by summarizing the current understanding of groundwater resources in the VCP aquifer system, derived primarily from the past three decades of cooperative scientific research and publication by DEQ and the U.S. Geological Survey (USGS).

Key Point #1

The confined Potomac aquifer is the largest and deepest in the VCP, accounting for 70% of total reported and estimated groundwater withdrawals in the Eastern Virginia Groundwater Management Area. The confined Yorktown-Eastover aquifer system accounts for 95% of total reported and estimated groundwater withdrawals in the Eastern Shore Groundwater Management Area. **Combining the two regulated areas, the major uses of groundwater are industrial (35% of total), private domestic (34%), and public water supply (26%).** See Sections 1.2.2 and 1.5 of report.

Key Point #2

The growing population of private domestic groundwater users in the VCP is projected to increase the total annual withdrawal rate by 200,000 to 300,000 gallons per day, on average, each year through 2050. These lawful, unpermitted withdrawals are not reported to DEQ. Instead, they must be estimated from census and water-use data. See Section 1.4.3 of report.

Previous studies have established hydrogeologic frameworks of the VCP aquifer system, including the smaller freshwater aquifer system of Virginia's Eastern Shore. These hydrogeologic frameworks define and describe the aquifers and confining units that constitute the aquifer system. Other previous investigations have characterized ambient groundwater quality, including the occurrence and potential movement of saltwater in the aquifer system. Periodically, these frameworks are adapted into numerical flow models that simulate historical and future groundwater levels; some also simulate the concentration of chloride in groundwater as an indicator of salinity. The published flow models are regularly updated to support DEQ's management of groundwater resources and to enable specific decisions about groundwater withdrawal permitting.

Key Point #3

Major withdrawals, especially at paper mills near Franklin and West Point, have caused inland groundwater levels to decline below sea level, altering the predevelopment flow pattern in the VCP. Multiple lines of evidence show that groundwater now tends to flow inward from the margins toward the withdrawal centers and downward from higher to lower units in the VCP aquifer system. See “[Historical Analysis of Withdrawals and Groundwater Levels](#)” (p. v), as well as Sections 1.4.4, 1.5.2 (esp. Table 4), 2.2, and 2.4.3 of report.

Key Point #4

These conditions cause land subsidence (sinking) and the potential for regional saltwater intrusion (saline water moving into freshwater aquifers). **Chloride concentrations in the aquifer system are increasing locally in some parts of Eastern Virginia and on the Eastern Shore.** See Sections 1.4.4 and 3.5.2 of report.

Building on the established history of cooperative research and publication, this report presents new analyses of historical and current data and trends, as well as future projections, relating to groundwater levels and groundwater quality. It also evaluates the potential future impacts of increasing groundwater withdrawals from newer industries such as data centers.

This report also describes the regulatory history and current framework for regulating groundwater withdrawals in the VCP under the Ground Water Management Act of 1992 and its implementing regulations. This history and the text of the Ground Water Management Act show that its purpose is to provide for the long-term preservation of groundwater supply in Eastern Virginia.

SJ 25 also directed DEQ to evaluate the effectiveness of the Ground Water Management Act of 1992 and to provide recommendations for consideration by the General Assembly. As detailed in the report, the Ground Water Management Act of 1992 has had mixed results. On the one hand, regional groundwater levels in the VCP broadly stabilized over the past decade; however, there are no areas of the VCP where a new large groundwater withdrawal could pass the technical evaluation criteria necessary to obtain a groundwater withdrawal permit.*

Regulatory History and Framework

From its inception until 1973, Virginia effectively had no groundwater regulation. During that time government involvement in groundwater withdrawals was limited to judicial decisions in disputes between parties who brought the matter to court. These decisions were based on common law, an unwritten court-made law that developed over years of judicial precedent.

In the latter half of the 20th century, the General Assembly concluded that this system was not adequate to protect the Commonwealth's groundwater resources. In response, it passed the Groundwater Act of 1973, but this act was eventually repealed and replaced by the Ground Water Management Act of 1992. This first attempt at regulating groundwater consumption created the concept of what we now know today as a groundwater management area. Under the Groundwater Act of 1973, these were known as "critical groundwater areas" and functioned much the same as today's analog by demarcating the regions in which the more stringent provisions of the act applied.

After nearly two decades, the General Assembly acknowledged that the Groundwater Act of 1973 was too permissive and did not sufficiently protect groundwater resources. The Ground Water Management Act of 1992 was designed to remedy the shortfalls of its predecessor and build on the lessons learned from implementing it to more effectively protect the Commonwealth's groundwater supply. This is the same act currently in effect today.

To assess the Ground Water Management Act of 1992's effectiveness, it is helpful to understand how it and its associated regulations work. At the most basic level, the act establishes a framework for the State Water Control Board to declare groundwater management areas in regulation. Currently there are two groundwater management areas, the Eastern Virginia Groundwater Management Area and the Eastern Shore Groundwater Management Area, which collectively cover most of Virginia east of Interstate 95. Within a groundwater management area, the Ground Water Management Act of 1992 requires certain entities to obtain a permit for groundwater withdrawals. For the permit requirement to apply, an entity must withdraw more than 300,000 gallons of groundwater in any one month (300,000 gallons in a month is approximately the amount of water used by 30 individual households) and not fall under one of the various statutory exceptions. To qualify for a permit, an entity must submit an application to DEQ detailing the proposed withdrawal and its use. The applicant must demonstrate that there is an existing or future need that this use would fulfill. In addition to this showing of need, the proposed withdrawal must also undergo a technical evaluation. DEQ's regulations require an evaluation of the proposed withdrawal's impact on groundwater levels and quality.** If the evaluation concludes that these impacts would be detrimental to existing users or to the overall concern for human consumptive uses, DEQ may deny that permit.

This technical evaluation relies on modeling the proposed withdrawal, and the models rely on data concerning existing withdrawals and groundwater supply. DEQ maintains an ever-growing network of observation wells to monitor groundwater levels across Virginia. These wells help DEQ make informed regulatory and

* See 9 VA. ADMIN CODE 25-610-110 D 3 h.

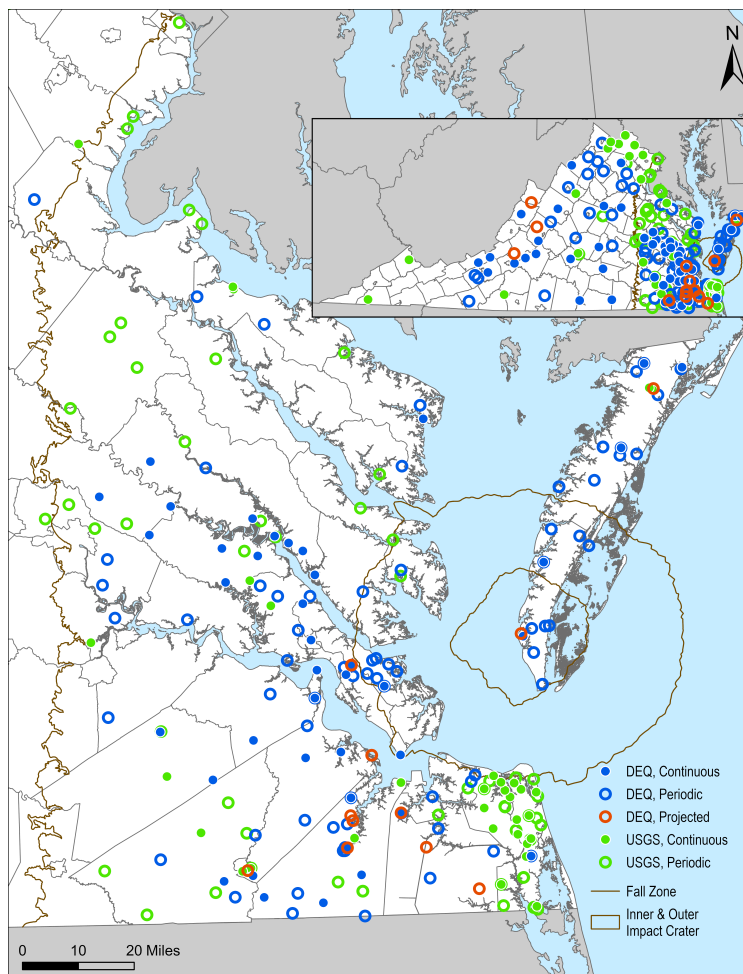
** See 9 VA. ADMIN CODE 25-610-110 D 2.

permitting decisions based on observed real-world conditions and the models these data help create. This statewide groundwater observation well network is described more fully in the next section.

Statewide Groundwater Observation Well Network

To monitor groundwater levels and quality, DEQ relies on the statewide groundwater observation well network (figure at right; Section 2.1.1 of full report). This network is a long-term, cooperative project of DEQ and the USGS Virginia and West Virginia Water Science Center. It consists of over 440 individual wells operated and maintained by DEQ or USGS staff. Some wells are grouped as multi-well research stations to monitor multiple aquifers, or multiple intervals within one aquifer. Some wells are dedicated to subnetworks for specific purposes, such as long-term climate (precipitation) response research, drought monitoring, or chloride (saltwater) monitoring. DEQ and USGS are currently expanding the statewide network, both in the VCP and in regions west of I-95, by installing new observation wells in a project funded by the General Assembly.

Each well in the statewide network is a scientific instrument carefully designed, constructed, and maintained to provide representative data from a known aquifer at a specific location and depth below land surface (and the corresponding elevation above sea level). Standard procedures govern the operation and maintenance of wells and the collection, analysis, and approval of data for publication. The resulting high-quality data sets flow into public-facing federal databases. The data support drought monitoring, water supply planning, and the management of groundwater resources. They also provide the foundation for VCP groundwater research, including this study.



Statewide groundwater observation well network. (See Figure 20.)

Historical Analysis of Withdrawals and Groundwater Levels

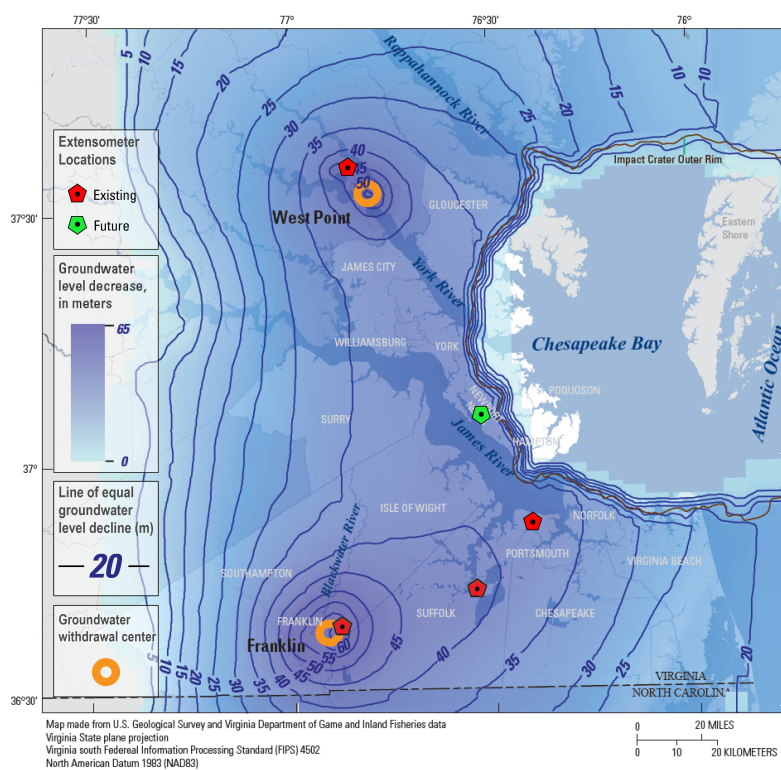
Key Point #5

The Franklin Mill closed in 2010 and partially reopened in 2012, causing a temporary rebound of groundwater levels that spread outward. From 2014 to 2017, DEQ undertook a special groundwater-management initiative. Consequently, the Potomac aquifer's annual overall groundwater deficit was reduced to nearly zero for about a decade. **Regional groundwater levels rose and broadly stabilized until about 2021. Rising trends then stalled and began to reverse as the temporary rebound spread, diminished, and was consumed by ongoing withdrawals across the region, including at the Franklin Mill. Under current conditions, groundwater levels throughout the Potomac aquifer are expected to enter a period of decline in the next five to ten years.** See Sections 2.2.2 and 2.3.2 of report.

The present-day groundwater conditions of the main-land VCP aquifer system are dominated by the effects of major inland withdrawals that have altered the predevelopment pattern of groundwater flow (Key Point #3, above). These longstanding withdrawals from the confined Potomac aquifer have caused two persistent regional “cones of depression” where the groundwater levels surrounding each pumping center decline towards the center (figure at right, courtesy of USGS; note that contours are in meters). The Potomac aquifer is the largest and deepest in the VCP, accounting for 87.8% of total reported groundwater withdrawals, or 70% of total reported plus total estimated groundwater withdrawals, in the Eastern Virginia Groundwater Management Area (annual average reported withdrawals, 2019–2023; estimated private domestic withdrawals based on 2020 census data). Within the affected areas, groundwater levels have declined below sea level.

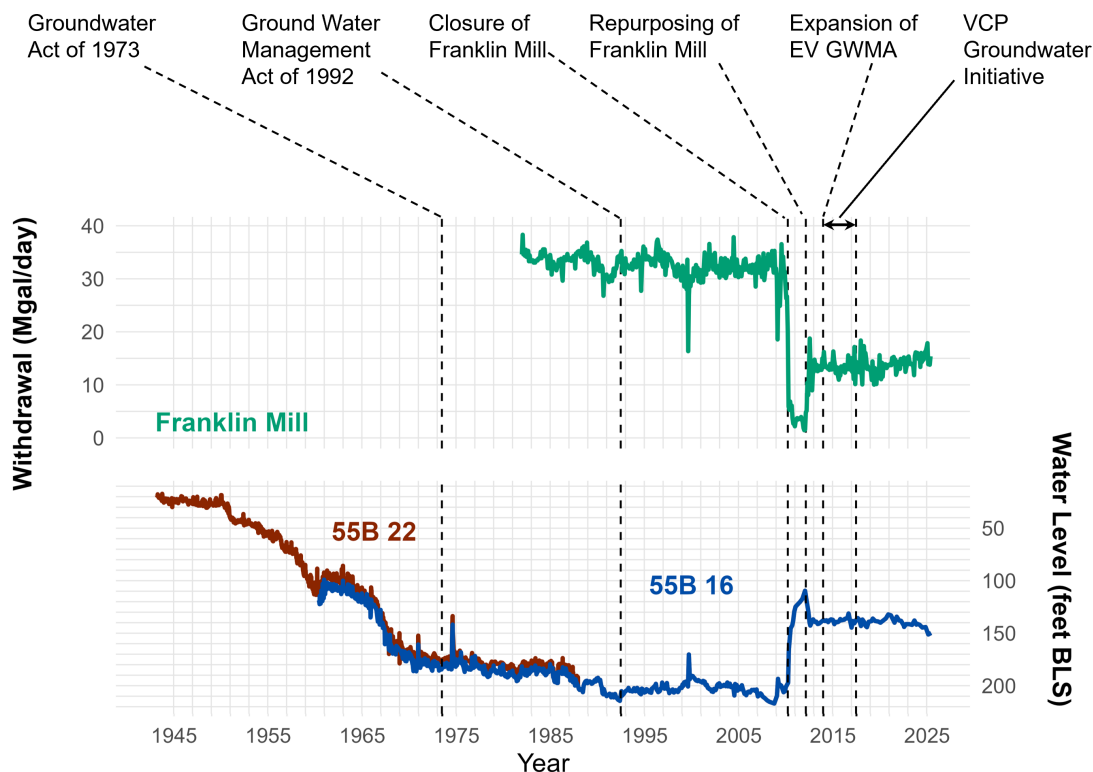
The cones of depression are centered on two historic Virginia paper mills, located near the City of Franklin and near the Town of West Point. A historical analysis of the mills' reported use and nearby groundwater levels showed that the total withdrawal rate varied widely over time, partly in response to changing economic and regulatory conditions. Franklin Mill data are shown in a figure on the next page (two panels of a larger figure within the report). In the decades before Virginia enacted its first management law, the Groundwater Act of 1973, groundwater levels near Franklin were declining at a rate that would have fallen below the top of the Potomac aquifer by around 1990. This would have begun dewatering the actual pore spaces of the confined aquifer, risking irreversible compaction of the aquifer sediments and permanent loss of groundwater storage.

The subsequent Ground Water Management Act of 1992 established the present-day regulatory frame-



Historical groundwater-level decline (contours in meters). (See Figure 10.)

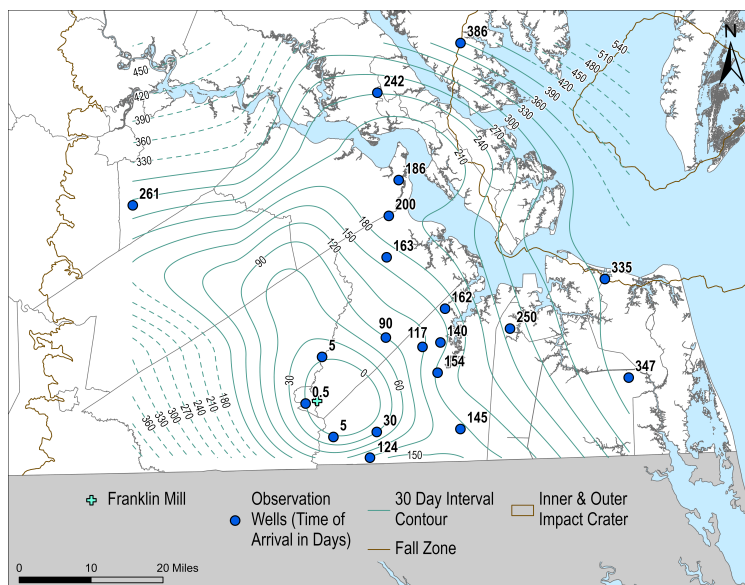
work, as outlined above. Until 2010, that framework generally ameliorated but did not reverse the broad, regional decline of groundwater levels in the Potomac aquifer. In 2010, closure of the Franklin Mill led to an 89% stepwise reduction of its Potomac-aquifer withdrawal. In 2012, the mill resumed operational withdrawal at 42% of the pre-2010 rate. The effect of this large net reduction in withdrawal was a rebound in the local and regional groundwater levels (figure below).



History of Franklin Mill withdrawals and nearby water levels, Potomac aquifer. (See Figure 24.)

The hydraulic pressure effects of the Franklin Mill closure propagated outward over time, resulting in a period of groundwater-level gains and broad stabilization across much of the Potomac aquifer. The figure at right illustrates the lateral spread of these effects through the middle zone of the Potomac aquifer, with numerical values and contours representing the elapsed time between the mill closure and the arrival of the hydraulic signal at specific observation wells.

This analysis demonstrated the utility of the statewide groundwater observation well network for detecting and measuring hydraulic events at multiple scales in the VCP aquifer system. The findings also highlighted the potentially wide-



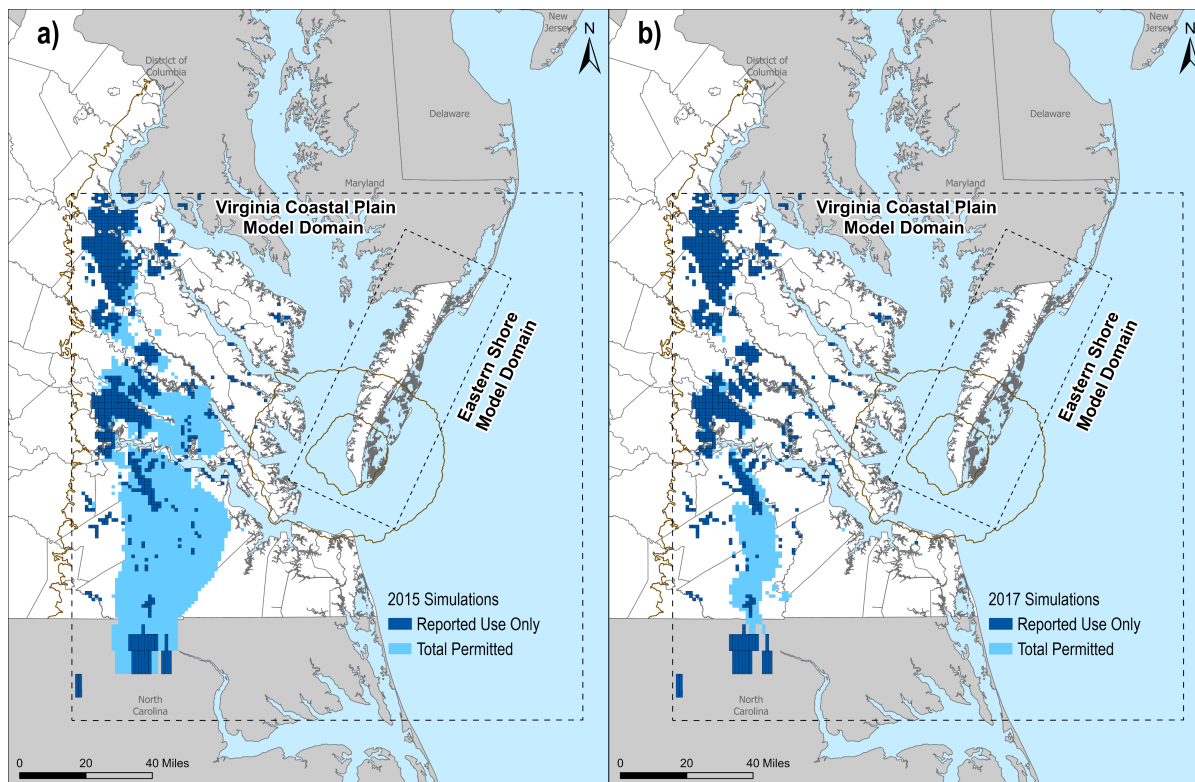
Contour map of elapsed time (days) from Franklin Mill closure to arrival of groundwater pressure effects. (See Figure 27.)

spread benefits of local reductions in major withdrawals. By analogy, widespread benefits could also result from major injections of treated water, but the data suggested that groundwater-level gains achieved through injection could be sensitive to operational disruptions or other reductions in the injection rate. Sustaining large-volume, long-term injections will involve technical challenges, as well as economic and political considerations.

Key Point #6

In the Potomac aquifer, hydraulic pressure effects travel tens of thousands of times faster than the typical flow of groundwater molecules through sediments. **Injections of water into the aquifer may yield a regional increase in groundwater levels with only local migration of the injected water molecules. However, regional water-level gains may dissipate rapidly when the injections cease.** This finding complicates the forecasting of groundwater levels that could result from aquifer replenishment, such as the Sustainable Water Initiative for Tomorrow (SWIFT). See Sections 2.2.4 and 2.6.1 of report.

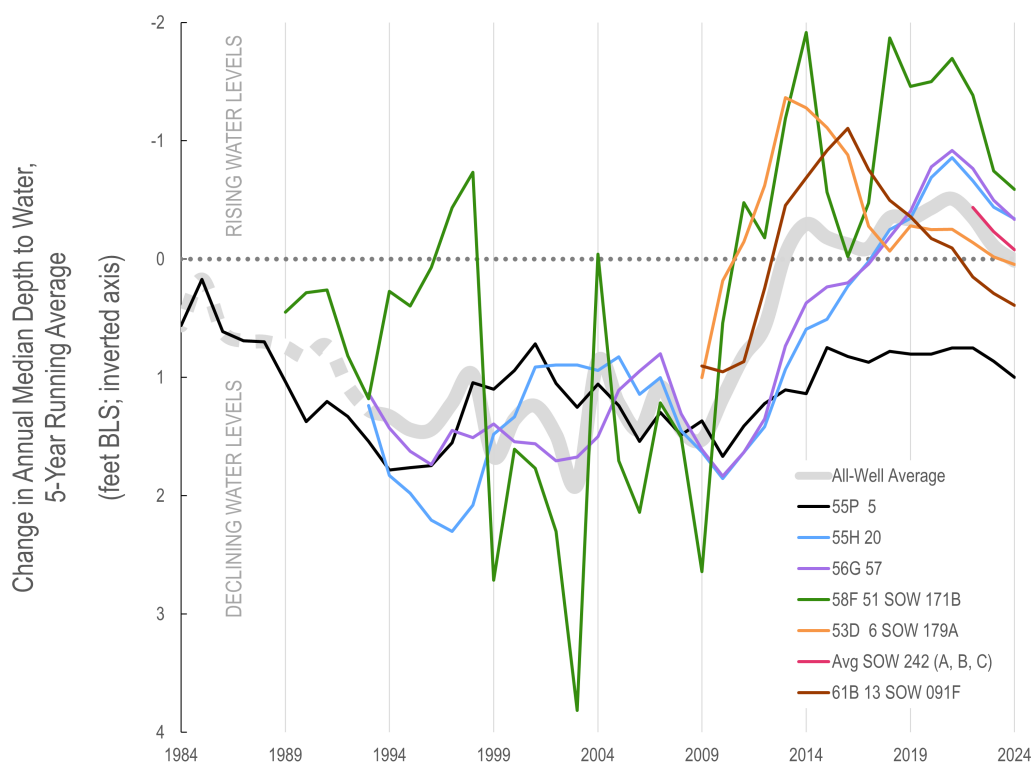
The stabilization of post-2010 gains in groundwater level was attributed in part to DEQ’s VCP Groundwater Initiative, which sought to reduce the historical over-allocation of the VCP groundwater resource. In the period from 2014 to 2017, DEQ negotiated lower maximum annual withdrawal limits for each of the top 14 permitted groundwater users. Before implementation of the initiative, these 14 facilities were permitted a combined maximum withdrawal equivalent to 146.54 million gallons per day; currently, the same 14 facilities are permitted a combined maximum withdrawal equivalent to 73.59 million gallons per day. As a result, the initiative achieved a notable decrease in the extent of mapped “critical cells” where DEQ’s groundwater model predicted unacceptably low groundwater levels (more than 80% of the vertical distance from the land surface to the aquifer top). The figure below illustrates the decrease, visible in the results of the 2017 “total permitted” simulations (light blue and dark blue areas combined). Since 2017, overall total reported groundwater usage has remained fairly level.



Extent of predicted critical cells (a) before and (b) after VCP Groundwater Initiative. (See Figure 17.)

Groundwater-Level Trends

Recent observational data suggests that groundwater levels across the Potomac aquifer mostly peaked or plateaued by 2021 and, in some cases, began to decline again. To evaluate these observations, DEQ completed a new analysis of five-year groundwater-level trends in selected wells across the Potomac aquifer (figure below). The results were consistent with the historical analysis described above. In the decades preceding 2010, groundwater levels were characterized by broad, consistent declines of a foot or two per year. Beginning in 2010 and progressing outward from the Franklin Mill facility mentioned above, the trends shifted towards a condition of rising water levels. The rate of groundwater-level rise peaked between 2013 and 2021, depending on the location. From 2021 to 2024, every analyzed well showed either a diminishing water-level rise or a growing decline. If this trend continues, all of the analyzed wells are projected to enter a condition of declining water levels within five to 10 years (Key Point #5, above).



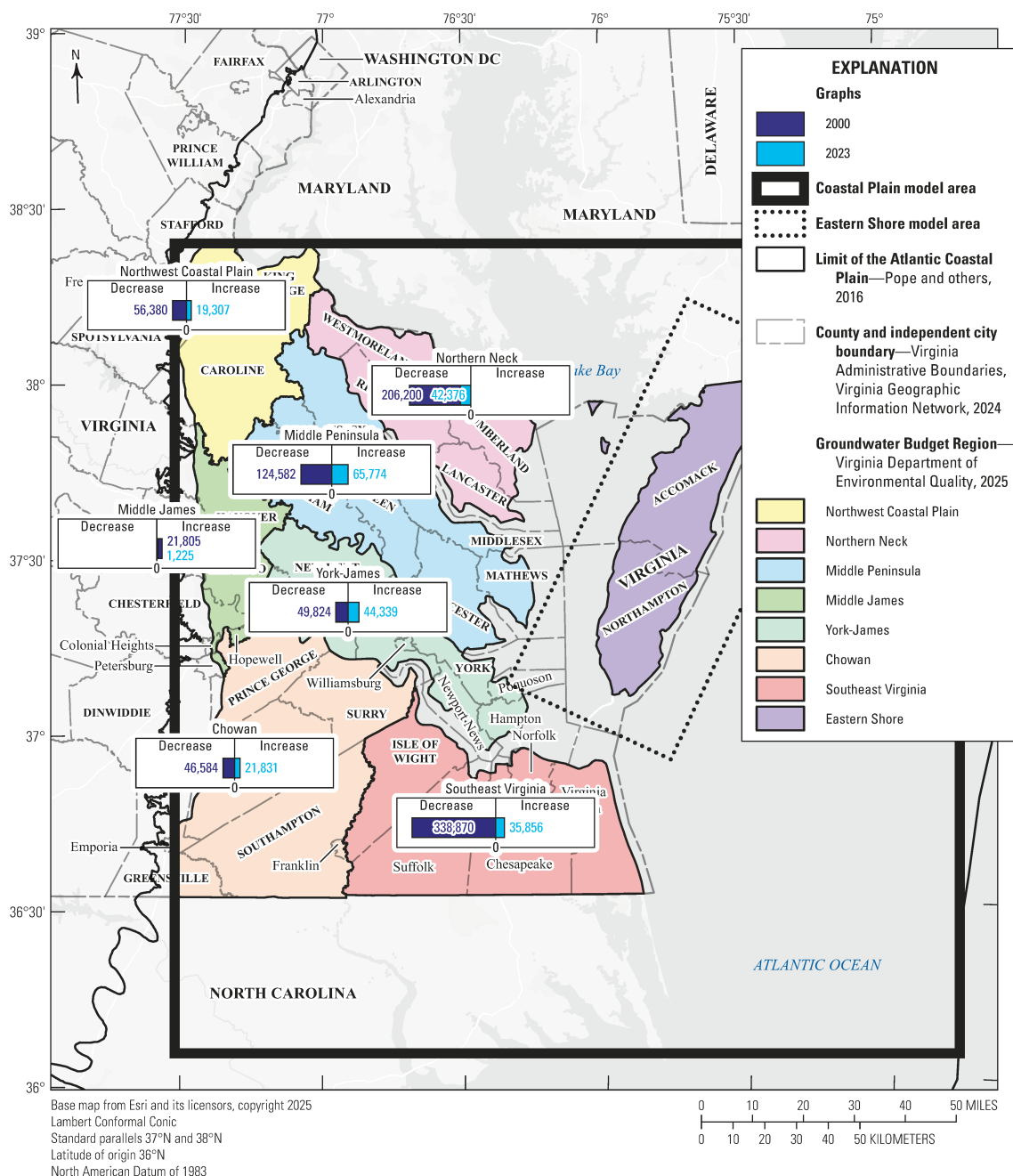
Groundwater-level trends in selected Potomac-aquifer observation wells. (See Figure 28.)

Regional Groundwater Budgets

Using established flow models, USGS analyzed the groundwater budget (inflows and outflows) for each of seven geographic regions within the mainland VCP and one additional region for the Eastern Shore. Within each of the eight regions, the analysis computed budgets for (1) the unconfined surficial aquifer, (2) the deepest confined aquifer, and (3) the combined group of all other hydrogeologic units (a simplification). In this way, the analysis considered the three-dimensional (geographic and vertical) conditions of the VCP aquifer system over the entire historical period since 1890 and into the future through 2073. The analyses focused on two years in the time series:

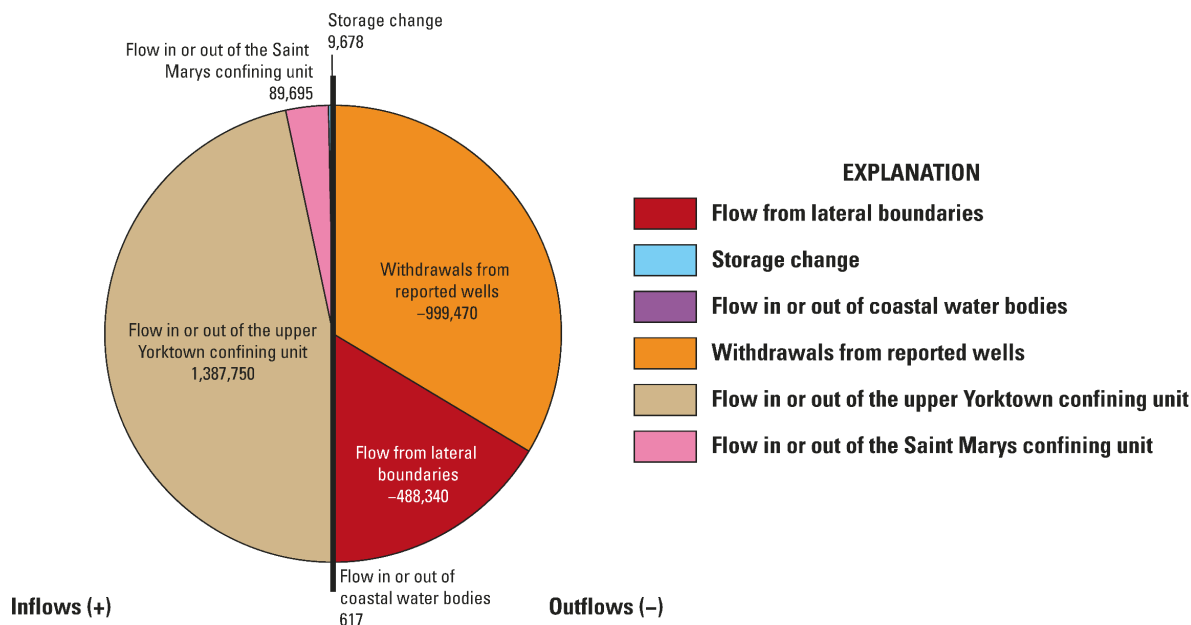
- **2000**, representing the period after implementation of the Ground Water Management Act of 1992 and before the 2010 reduction in Franklin Mill withdrawals, and
- **2023**, representing current conditions, which have remained relatively stable since the hydraulic effects of the 2010 reduction spread across the region.

The results corroborated other findings that historical and ongoing groundwater extraction has fundamentally altered groundwater flow from predevelopment conditions (Key Point #3, above). Historical and ongoing withdrawals from deeper aquifers, including the Potomac aquifer, have induced substantial downward flow from overlying units. During the time when VCP groundwater withdrawal rates were near the historical maximum, downward leakage from the overlying portion of the confined aquifer system offset nearly 40% of the total withdrawals from the Potomac aquifer. Lower rates of withdrawal since 2010 allowed a recovery of groundwater storage in the Potomac aquifer, as illustrated in the figure below that compares rates of storage change in 2000 and 2023. Despite the general increase in Potomac aquifer storage, the VCP model domain as a whole continued to show a small rate of storage decrease.



Comparison of regional groundwater storage rates in Potomac aquifer, 2000 and 2023. Values in cubic feet per day. (See Figure 30.)

The budget analysis also indicated that groundwater tends to flow from peripheral regions toward the central regions where the largest withdrawals occur. These inward flows suggested the potential for saltwater intrusion. On the Eastern Shore, the rate of withdrawal is near its historical maximum. The groundwater budget for the Yorktown-Eastover aquifer system of the Eastern Shore indicates a small rate of inflow of presumably saline groundwater from the underlying confining unit and from coastal water bodies (figure below). The potential for saltwater migration was considered further in the groundwater-quality portion of this study, which is described below.



Simulated yearly groundwater budget, Yorktown-Eastover aquifer system, Eastern Shore, 2023. Values in cubic feet per day. (See Figure 35.)

Future Impacts of Newer Industries

In 2024, industrial users in the groundwater management areas reported a combined groundwater withdrawal rate of nearly 36 million gallons per day, on average. This amount represented over half of all reported groundwater withdrawals in the management areas that year. Among the top 14 annual groundwater withdrawals, the two largest groundwater users were industrial facilities, reporting combined withdrawals of 28.9 million gallons per day. Three other industrial users were also among the top 14 facilities in the groundwater management areas in 2024. These five facilities represented established industries, namely the production of paper, specialty chemicals, and poultry.

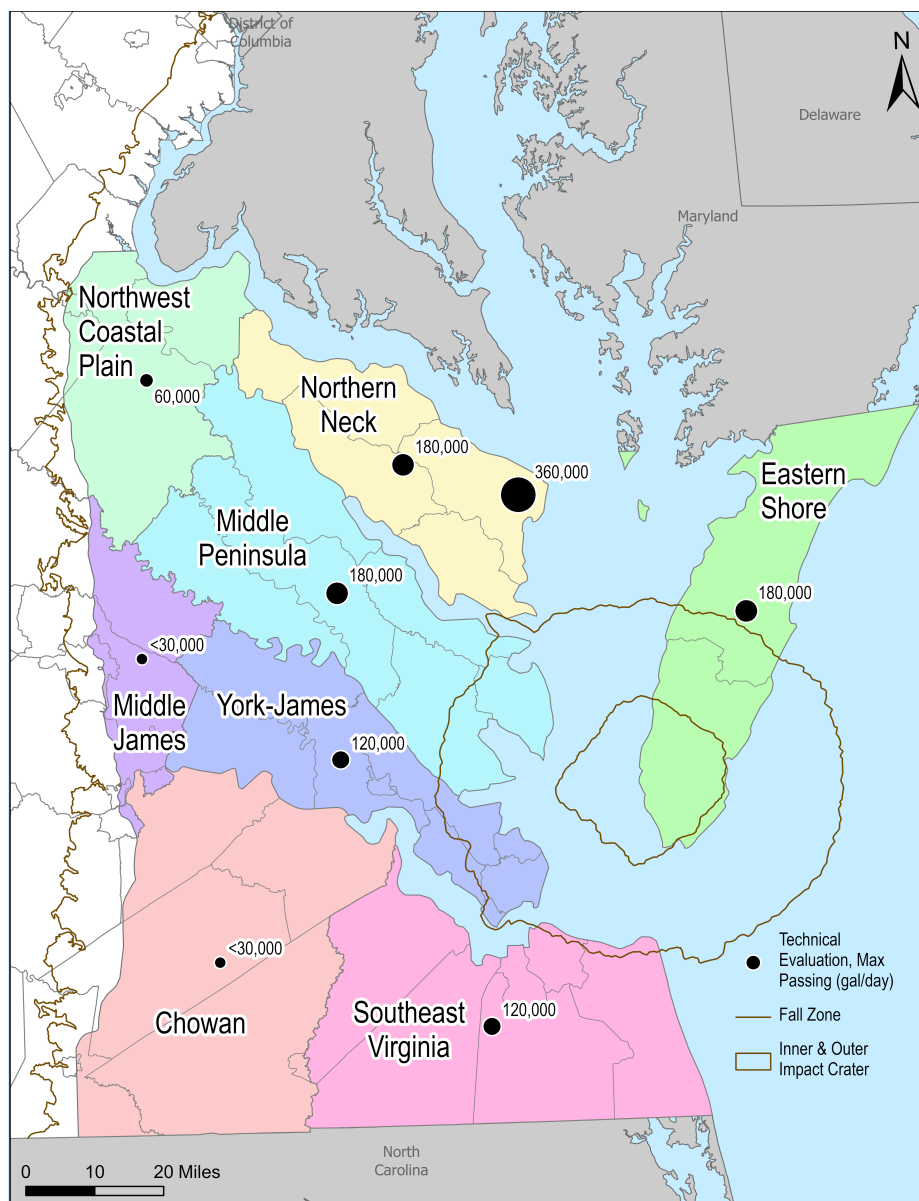
To assess the potential future impacts of groundwater withdrawals from newer industries such as data centers, DEQ hypothesized a major withdrawal of 3 million gallons per day at the centroid of each groundwater budget region (figure on next page). One additional location was selected in Northumberland County to represent favorable hydrogeological conditions for a large withdrawal. A separate technical evaluation of each hypothetical withdrawal determined that none would pass the evaluation criteria to receive a permit under Virginia's Groundwater Withdrawal Regulations.

A maximum-passing withdrawal was computed for each location. The results varied from 360,000 gallons per day in Northumberland County to less than 30,000 gallons per day (the lower limit of analysis) in Henrico County and Sussex County (same figure on next page). These relatively low amounts suggest that, under current conditions, the VCP aquifer system has limited capacity to add significant withdrawals. Only the upper end of the estimated range would support a typical hyperscale data center with evaporative cooling,

but the Northumberland County location of the upper estimate is far from existing areas of data-center development. Capacity appears minimal in the western regions of the VCP, near the I-95 corridor where denser infrastructure is available to support development.

Key Point #7

Under current conditions, the VCP aquifer system has limited capacity for significant new withdrawals. The estimated capacity for new withdrawals varies by region, from a maximum of 360,000 gallons per day in the eastern Northern Neck to less than 30,000 gallons per day in some western regions near I-95. Only the upper end of this range would support a significant new withdrawal for industrial use. See Section 2.5.4 of report.



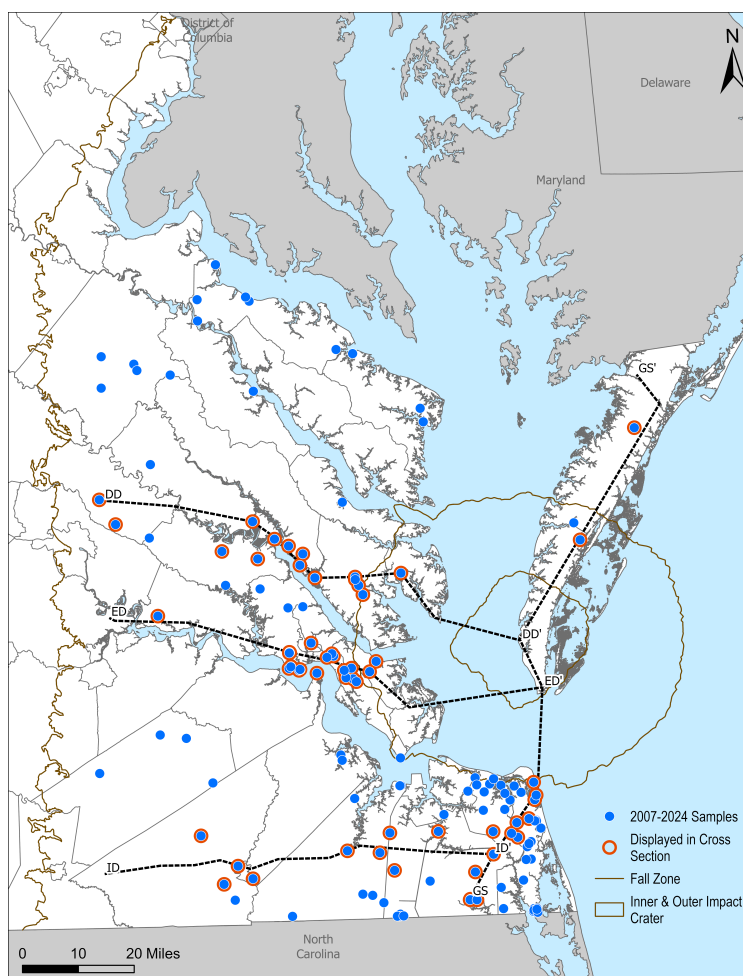
Maximum withdrawal (gallons per day) projected to meet criteria for a groundwater withdrawal permit. Groundwater budget regions for reference. (See Figure 37.)

Groundwater Quality

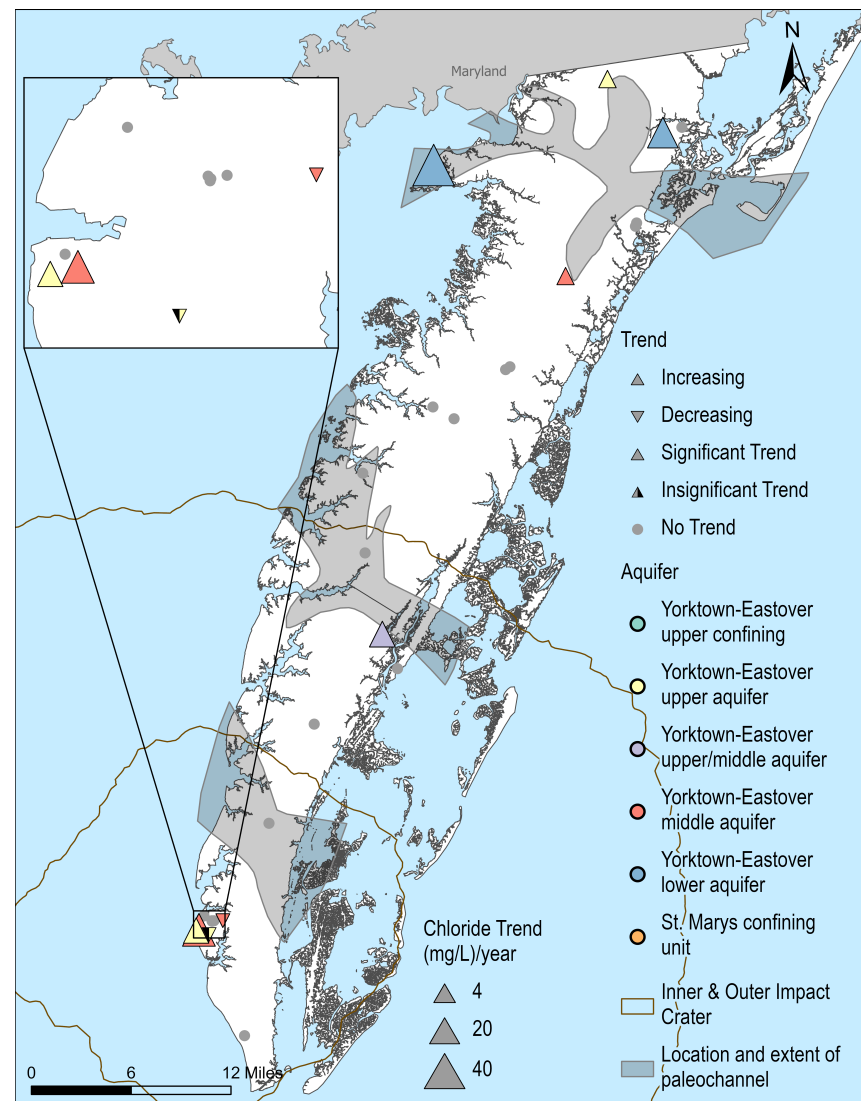
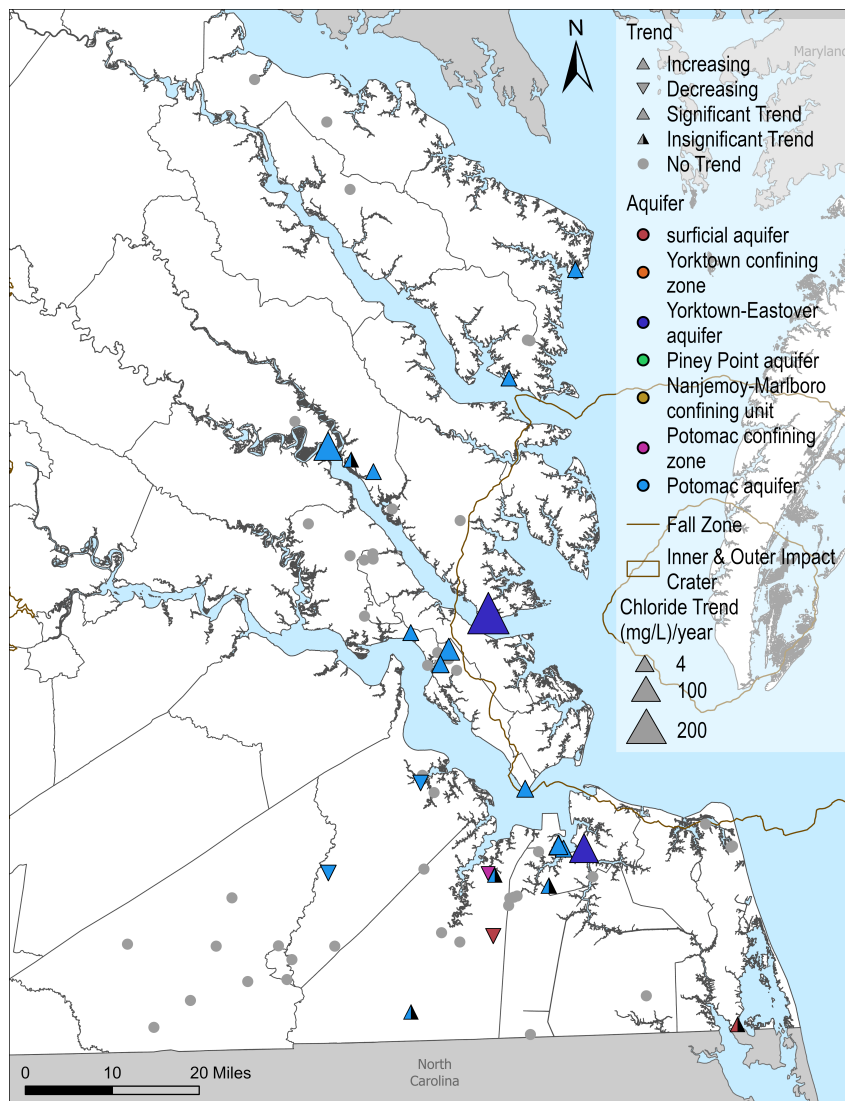
DEQ compiled and analyzed the available groundwater-quality data collected in the VCP since 2007 (figure at right). This effort updated and expanded a major study of VCP groundwater quality published by USGS in 2010. A comparison of the two data sets, 1906–2007 and 2007–2024, revealed consistency in regional-scale groundwater chloride concentrations, in the overall position of the saltwater-transition zone, and in the extent and sequence of hydrochemical facies (three-dimensional zones of groundwater with broadly similar chemical characteristics, representing the evolution of groundwater as it gradually flows through the VCP aquifer system). The results demonstrated that regional groundwater quality has not changed appreciably since 2007 and confirmed that spatial trends have remained generally stable since the early 20th century.

The new groundwater-quality analysis did identify locally increasing chloride concentrations in some parts of Eastern Virginia and on the Eastern Shore (figures on next page; Key Point #4, above). The trend analysis was applied to each well that offered a suitable data set, regardless of the sample period; therefore, the results include wells that

exhibited trends in the past, as well as in the present day. Most of the observed increases were attributed to the influence of specific nearby withdrawals. Overall, the trends in chloride concentration were consistent with evidence from the regional groundwater budget analyses, noted above. Some locations with increasing trends, notably near Chincoteague on the Eastern Shore and near West Point in Eastern Virginia, coincided with areas where known withdrawals have caused groundwater levels to decline below sea level, creating conditions that would favor lateral saltwater intrusion. However, even under favorable conditions, lateral migration may be delayed significantly by the generally slow rate of groundwater flow. For these reasons, it was difficult to distinguish whether the observed local trends were transitory, as opposed to indicating a potentially broader, long-term shift in the regional saltwater-transition zone. In the future, aquifer-replenishment operations such as SWIFT may cause significant groundwater-level changes that could also induce local or regional changes in aquifer salinity. DEQ's chloride-monitoring strategy, developed in cooperation with USGS, is designed to collect new data for additional evaluation of these issues (Section 1.4.5).



Locations of VCP groundwater sample collection, 2007–2024.
(See Figure 40b.)



Groundwater sample locations with chloride concentration trends in Eastern Virginia (left; see Figure 48b) and on the Eastern Shore (right; see Figure 49b).

Effectiveness and Recommendations

Key Point #8

The Ground Water Management Act of 1992 has achieved mixed results. The regulatory framework enabled the Commonwealth to stabilize groundwater-level gains that resulted from the unrelated closure of the Franklin Mill in 2010. However, groundwater supply east of I-95 is constrained, and current projections indicate declining availability in the near future. See Section 4 of report.

The goal of the Ground Water Management Act of 1992 is to provide for the long-term preservation of groundwater supply. The Ground Water Management Act of 1992 provided the framework to establish the Eastern Virginia Groundwater Management Area and the Eastern Shore Groundwater Management Area. Collectively these two areas cover most of Virginia east of I-95. Within these groundwater management areas DEQ-issued permits are required to withdraw 300,000 gallons or more in any one month. This study shows that regulation can and does have a measurable effect on groundwater trends. In many areas of the VCP, water levels did stabilize during the past decade. However, that effect is currently somewhat limited, and more recent observation data indicates that water levels may be starting to decline. Of more immediate concern, this report shows that the VCP aquifer system cannot currently support further permitted significant withdrawals.

To address these issues DEQ offers five recommendations:

1. The General Assembly should amend the Ground Water Management Act of 1992 to:
 - a. Codify the existing regulatory language providing that DEQ has the authority to deny an application for a permit for a new, expanded, or renewed withdrawal in a groundwater management area if “[t]he cumulative stabilized impact of the proposed withdrawal in combination with all existing lawful withdrawals will lower water levels in a confined aquifer below a point that represents 80% of the distance between the land surface and the top of the aquifer.” (Recommendation #1)
 - b. Clearly provide DEQ with the authority to deny an application for a groundwater withdrawal permit or to reduce the permitted withdrawal volume where alternative water sources, such as surface water or water reuse, are reasonably available. (Recommendation #2)
 - c. Clarify how the prioritization for human consumption and the goal of protecting existing uses should be reconciled and implemented through permit decisions. (Recommendation #3)
 - d. Prohibit DEQ from issuing any permits for new significant withdrawals in portions of groundwater management areas located outside the extent of the applicable groundwater flow model. (Recommendation #7)
2. The General Assembly should amend Chapter 22 of Title 15.2 of the Code of Virginia to require local comprehensive plans in groundwater management areas to limit planned growth based on groundwater availability if no other water supply is feasible. (Recommendation #5)
3. Any legislation to amend the Groundwater Management Act of 1992 to authorize groundwater trading should first address:
 - a. The scientific and technical consensus on the safety and reliability of groundwater trading.
 - b. The protection of the public right to groundwater resources.
 - c. Resolution of how groundwater rights are allocated.
 - d. Whether and how to compensate parties providing the recharge of the aquifer.
 - e. Appropriation of adequate funds to support the development of a groundwater trading regime and a budgetary plan to pay for oversight.(Recommendation #11)

4. The General Assembly should appropriate \$1,020,000 in Fiscal Year (FY) 2027 and \$720,000 in FY 2028 to DEQ for five full time equivalents (FTEs) and the projects specified below to more effectively implement the Ground Water Management Act of 1992:
 - a. \$135,000 per year for 1 FTE to help coordinate, analyze, and act on data regarding the aquifer system and groundwater withdrawals, including lawful unpermitted groundwater withdrawals. (Recommendation [#4](#))
 - b. \$270,000 per year for 2 FTEs to enhance DEQ's groundwater withdrawal permitting compliance program. (Recommendation [#6](#))
 - c. \$270,000 per year for 2 FTEs to improve the characterization of the VCP aquifer system, enhancing DEQ's ability to conduct technical evaluations. (Recommendation [#8](#))
 - d. \$45,000 per year to purchase real-time monitoring equipment for observation wells to better understand changing groundwater conditions in the VCP, including the recharge effects of HRSD's SWIFT Project. (Recommendation [#9](#))
 - e. \$300,000 to hire a contractor to study and evaluate other locations in the Commonwealth that could benefit from aquifer recharge projects similar to HRSD's SWIFT Project after the extent and magnitude of the full recharge volume is realized. (Recommendation [#10](#))
5. In addition to increasing general fund allocations, the General Assembly should raise the statutory limit on groundwater withdrawal permit fees to an amount sufficient to initially cover at least 50% of program costs. (Recommendation [#12](#))

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List of Abbreviations

Abbreviation	Definition
AOI	area of impact
BLS	below land surface
BMSL	below mean sea level
CRN	Climate Response Network
DEQ	Virginia Department of Environmental Quality
DMTF	Virginia Drought Monitoring Task Force
EPA	United States Environmental Protection Agency
FTE	full time equivalent
gal/day	gallons per day
GBR	groundwater budget region
GIS	Geographic Information System
GPS	Global Positioning System
GWI	Groundwater Initiative
GWMA	groundwater management area
HRSD	Hampton Roads Sanitation District
I-95	Interstate 95
JLARC	Joint Legislative Audit and Review Commission
L/kWh	liters per kilowatt-hour
LLC	limited liability company
MAR	managed aquifer recharge
mg/L	milligrams per liter
mg/L/yr	milligrams per liter per year
Mgal	millions of gallons
MK	Mann-Kendall
MW	megawatts
NASA	National Aeronautics and Space Administration
N	number (sample size)
NOAA	National Oceanic and Atmospheric Administration
NWIS	National Water Information System
p-value	probability value
S or S-Statistic	Mann-Kendall sum of difference/trend statistic
SJ 25	Senate Joint Resolution No. 25 (2024 Session)
SOW	State Observation Well
STORET	Storage and Retrieval system
SWIFT	Sustainable Water Initiative for Tomorrow
TS	Theil-Sen
USGS	United States Geological Survey
VAHydroGW-ES	Regularly updated version of the Virginia Eastern Shore groundwater flow model
VAHydroGW-VCPM	Regularly updated version of the Virginia Coastal Plain groundwater flow model
VCP	Virginia Coastal Plain
VDH	Virginia Department of Health
WCMP	water conservation and management plan
WQP	Water Quality Portal
WUE	Water Usage Effectiveness

Glossary of Terms

(Note: In each major section of the report, the first occurrence of each term below is marked in **bold font**.)

Term	Definition
Aquifer	A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield usable quantities of water to wells and springs. (Driscoll, 1986)
Aquifer, confined	An aquifer constrained above and below by impermeable beds or beds of markedly lower permeability than the aquifer material; confined groundwater is generally subject to pressure greater than atmospheric. (Driscoll, 1986)
Aquifer, unconfined	An aquifer where the water table is exposed to the atmosphere through openings in the overlying materials; a water-table aquifer. (Driscoll, 1986)
Cone of depression	A depression in the groundwater table or potentiometric surface that has the shape of an inverted cone and develops around a well from which water is being withdrawn. It defines the area of influence of a well. (Driscoll, 1986)
Confining unit	A low permeability hydraulically continuous fine-grained hydrogeologic unit that impedes horizontal groundwater flow and only allows very slow vertical leakage of groundwater. (McFarland and Bruce, 2006)
Confining zone	A fine-grained interbed or group of interbeds that approximates the transition from an aquifer to an adjacent aquifer or confining unit. (McFarland and Bruce, 2006)
Cross-section	An illustrative diagram showing geologic or hydrogeologic features transected by a vertical plane. (Bates and Jackson, 1987)
Drill cuttings	Geologic material displaced and returned to the land surface by the drilling process. Used by DEQ geologists to create lithologic logs and to characterize the properties and relative positions of hydrogeologic units.
Dewatering	The water level in a confined aquifer falling below the aquifer top resulting in an unconfined condition.
Extensometer	An instrument that measures the change in thickness of a specified depth interval, used to monitor the compaction and expansion of the aquifer system.
Facies	The aspect, appearance, and characteristics of a geologic unit, usually reflecting the conditions of its origin; especially differentiating it from adjacent or associated units. Hydrochemical facies are bodies of water with separate but distinct chemical compositions contained in an aquifer. (Bates and Jackson, 1987)
Fault	A fracture or a zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture. (Driscoll, 1986)
Geomorphology	The science that studies the general configuration of the Earth's surface; specifically the classification, description, nature, origin, and development of landforms and their relationships to underlying structures, and the history of geologic changes as recorded by these surface features. (Bates and Jackson, 1987)
Heterogeneous	Nonuniform in structure or composition throughout. (Driscoll, 1986)
Hydraulic conductivity	The rate of flow of water in gallons per day through a cross section of one square foot under a unit hydraulic gradient, at the prevailing temperature. (Driscoll, 1986)
Hydraulic gradient	The rate of change in total head per unit of distance of flow in a given direction. (Driscoll, 1986)
Hydraulic head	Energy contained in a water mass, produced by elevation, pressure, or velocity; the height to which water will freely rise in a well or standpipe. (Driscoll, 1986)
Hydrogeology	The study of the interrelationships of geologic materials and processes with water, especially groundwater. (Fetter, 2000)
Infiltration	The flow of a water into solid substances through pores or small openings; specifically the movement of water into soil, sediments, or rocks. (Bates and Jackson, 1987)
Intrusion	The density or gradient driven migration of groundwater resulting in a measurable change in the chemistry. Lateral intrusion into an aquifer system is typically regional, such as saltwater intrusion, and generally operates on geologic timescales. Unlike lateral intrusion, vertical intrusion is generally localized. Vertical intrusion is commonly, but not exclusively, a result of induced flow from of pumping (see <i>Upconing</i>).

(continued on next page)

Term	Definition
Iso-concentration	Having or representing an equal concentration of a specified chemical constituent; said of a line or surface.
Leakage	The transmission of water into or out of an aquifer through adjacent semi-permeable layers, known as confining units. This process is also known as cross-formational flow. (Driscoll, 1986; Fetter, 2000)
Lithology	The description of rocks or geologic units, especially in hand specimen and in outcrop, on the basis of such characteristics as color, mineralogic composition, and grain size. (Bates and Jackson, 1987)
Observation well	A well built or designated for the purposes of hydrological observation, usually of ground-water levels, as part of a site-scale pump test or a regional-scale monitoring network. Used interchangeably in text with “monitoring well,” which can sometimes specify a well built or designated for groundwater-quality monitoring.
Paleochannel	Former river or stream channel that has been buried or filled with younger sediments that have different hydrogeologic characteristics than the surrounding strata. Can act as preferential pathways for groundwater flow.
Potentiometric surface	The surface representative of the level to which water will rise in a well cased/screened in a confined aquifer. (Fetter, 2000)
Reservoir	Subsurface rock, regolith, or other sediments that are saturated with water; an aquifer. (Bates and Jackson, 1987)
Screened interval	A section of well casing with openings and a filtering device used to keep sediment from entering a well while allowing groundwater to enter the well; well screen. (Driscoll, 1986)
Storage, groundwater	Generally, the volume of water contained in an aquifer or group of hydrogeologic units. Groundwater budgets compute flows that represent net changes in storage; a storage decrease is represented with a positive sign because this represents a source of water to the budget, while a storage increase is represented with a negative sign. (Pope et al., 2026)
Stratigraphy	(1) The arrangement of layers (strata) as to geographic position and chronologic order of sequence. (2) The science of rock strata (layers). It is concerned with all characteristics of layers and their interpretation in terms of origin and geologic history. (Bates and Jackson, 1987)
Subsidence	Sinking or downward settling of the Earth’s surface, not restricted in rate, magnitude, or area involved. (Bates and Jackson, 1987)
Upconing	Vertical migration of the freshwater-saltwater interface upwards toward a pumping well due to lowered freshwater head resulting from the cone of depression. (Heath (1983) and McFarland (2015))
Water table	The surface between the vadose zone and the groundwater; that surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere. (Driscoll, 1986)

List of Web Resources

Description	Link
DEQ Resources	
Drought Monitoring	https://www.deq.virginia.gov/our-programs/water/water-quantity/drought/
Groundwater Characterization and Monitoring	https://www.deq.virginia.gov/water/water-quantity/groundwater-characterization-and-monitoring-program
Ground Water Withdrawal Permitting	https://www.deq.virginia.gov/water/water-withdrawal/ground-water
Water Supply Planning	https://www.deq.virginia.gov/our-programs/water/water-quantity/water-supply-planning
USGS Resources	
Climate Response Network	https://www.usgs.gov/mission-areas/water-resources/science/climate-response-network
Eastern Shore Groundwater Wells Map	https://va.water.usgs.gov/webmap/groundwater-wells-es/
VA and WV Groundwater Trends Dashboard	https://rconnect.usgs.gov/vawv-groundwater/
Virginia Extensometer Network	https://www.usgs.gov/centers/virginia-and-west-virginia-water-science-center/science/virginia-extensometer-network

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Some of the analyses presented in Section 2 were initially undertaken to address questions from the Potomac Aquifer Recharge Oversight Committee that were not directly related to Senate Joint Resolution No. 25. These questions prompted a series of wide-ranging technical discussions in late 2024. DEQ's preliminary analyses benefited from the comments of the committee members and other participants in these discussions.

Most of the DEQ staff listed above, as well as the contributions from USGS and Aquaveo, were supported by DEQ general funds from the General Assembly. Some of these funds were specified for the purpose under the budget amendments of the 2024 Session for the 2025–2026 biennium: Item 363 #6c provided \$100,000 each year to increase groundwater technical capacity and complete a study of the groundwater supply in the Commonwealth, pursuant to Senate Joint Resolution No. 25. In addition, Item 363 #3c provided \$135,000 each year and one position to support monitoring of new state observation wells installed by the USGS; this item enabled a reorganization of the Groundwater Characterization and Monitoring Program that allowed multiple staff to participate in the SJ 25 groundwater study and report. Finally, one DEQ contributor's position was fully supported by the U.S. Environmental Protection Agency, through its Performance Partnership Grant to DEQ under section 106 of the Clean Water Act (33 U.S. Code §1256). DEQ gratefully acknowledges these funding sources.

1 Introduction

1.1 Purpose and Scope

In the 2024 Session of Virginia's General Assembly, Sen. Richard H. Stuart of Senate District 25 introduced Senate Joint Resolution No. 25 (SJ 25), which went on to pass both the Senate and the House of Delegates. The text of the joint resolution as passed can be found in Virginia's Legislative Information System. In full, it reads as follows:

SENATE JOINT RESOLUTION NO. 25

Requesting the Department of Environmental Quality to study the groundwater supply in the Commonwealth east of Interstate 95. Report.

Agreed to by the Senate, March 5, 2024

Agreed to by the House of Delegates, March 4, 2024

WHEREAS, the General Assembly recognizes the critical importance of ensuring a safe and sustainable drinking water supply for its citizens; and

WHEREAS, the Ground Water Management Act of 1992 has served as a foundational framework for the regulation and management of groundwater resources in the Commonwealth; and

WHEREAS, the Commonwealth has experienced changes in its population, industrial development, and technological advancements over the past three decades; and

WHEREAS, it is imperative to assess the effectiveness of the existing regulatory framework in addressing the current and future challenges to the Commonwealth's groundwater supply; and

WHEREAS, newer industrial activities such as data centers have the potential to significantly impact groundwater resources, and it is essential to evaluate the historical, current, and potential future impacts of such activities on the Commonwealth's groundwater supply; now, therefore, be it

RESOLVED by the Senate, the House of Delegates concurring, That the Department of Environmental Quality be requested to study the groundwater supply in the Commonwealth east of Interstate 95.

In conducting its study, the Department of Environmental Quality shall (i) provide historical and current data and trends relating to groundwater levels and groundwater quality; (ii) to the extent that dedicated funds are available, include future projections for groundwater levels and groundwater quality; (iii) to the extent that dedicated funds are available, evaluate potential future impacts to the groundwater supply as a result of increasing groundwater withdrawals from newer industries such as data centers; (iv) assess the current regulatory effectiveness of the Ground Water Management Act of 1992 (§ 62.1-254 et seq. of the Code of Virginia); and (v) consider and recommend any amendments to the Ground Water Management Act of 1992. If sufficient dedicated funds are not available to fully complete the necessary analysis, the Department of Environmental Quality's report shall include an estimate of the amount of additional funding necessary to complete its analysis.

Technical assistance shall be provided to the Department of Environmental Quality by the State Water Control Board. All agencies of the Commonwealth shall provide assistance to the Department of Environmental Quality for this study, upon request.

The Department of Environmental Quality shall complete its meetings by November 30, 2025, and shall submit to the Governor and the General Assembly an executive summary and a report of its findings and recommendations for publication as a House or Senate document. The executive summary and report shall be submitted as provided in the procedures of the Division of Legislative Automated Systems for the processing of legislative documents and reports no later than the first day of the 2026 Regular Session of the General Assembly and shall be posted on the General Assembly’s website.

Having completed its study, DEQ submits this report to fulfill the General Assembly’s request. The joint resolution enumerates five items, (i) through (v), to be included in the study. To address these items efficiently, the report is organized into four main sections. Section 1 introduces the purpose and scope of the report, describes the study area, reviews the history of the statutory and regulatory framework, and summarizes relevant previous investigations that provide the scientific foundation for this study and report. Section 2 encompasses items (i), (ii), and (iii) in relation to groundwater levels, including historical and current data and trends, future projections, and potential future impacts to the groundwater supply as a result of increasing groundwater withdrawals from newer industries such as data centers. Section 3 considers items (i), (ii), and (iii) in relation to groundwater quality. Section 4 addresses item (iv) by assessing the current regulatory effectiveness of the Ground Water Management Act of 1992¹ and item (v) by considering and recommending possible amendments to the Act.

1.1.1 How Much Groundwater?

How much groundwater supply is available in the Commonwealth east of Interstate 95 (I-95)? At first, it seems like a simple question that should have a simple answer. If the **aquifer** system were like a tank, with fixed walls and an overall water level, then the water level could be measured and the total volume calculated. If there were measurable inflows and outflows, then the future volume could be predicted and allocated accordingly. The water could be considered as one continuous body, such that a removal from one part of the tank could be offset instantly by the addition of an equal volume somewhere else.

In reality, the Virginia Coastal Plain (VCP) aquifer system is none of the above. Instead, it is complex, composite, discontinuous, and hidden underground. Many inflows and outflows cannot be measured directly but must be estimated or simulated. When conditions change, the aquifer system takes time to respond, and the effects vary in space across local and regional scales. Large and persistent stresses can affect not only the groundwater levels but the aquifer material itself. Because of these dynamic features, the system’s current conditions represent one moment in a long history that must be understood before future conditions can be predicted.

For these reasons, DEQ and the U.S. Geological Survey (USGS) have carried out a decades-long program of cooperative scientific investigation, including data collection, analysis, and modeling, to support the effective management of groundwater resources in the VCP (Figure 1). This report summarizes the aquifer system’s current conditions in the context of multiple histories: geological, economic, and regulatory. The sections below also use current trends to project the future conditions of the system. Although there is no simple answer, this report represents, to date, the most comprehensive

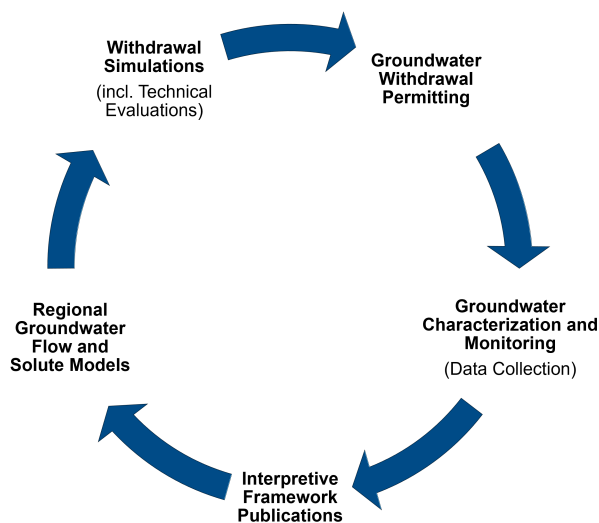


Figure 1: Generalized cycle of cooperative scientific investigation and groundwater-resource management.

¹See VA. CODE ANN. § 62.1-254 et seq.

effort to address the question of how much groundwater supply is available in this important region of the Commonwealth.

1.1.2 Limitations

The scope of this report is broad, but certain limitations are necessary. First, the geological study of the VCP aquifer system dates back 160 years. This report summarizes the current state of the science, derived mainly from the past 30 years of cooperative investigation and publication by DEQ and USGS. The earlier history of VCP research is generally beyond the scope of this report.

The study is also limited by the availability and density of data, which vary across the study area. In certain marginal areas of the VCP, the **hydrogeology** has not been thoroughly characterized and, in some cases, may present a special challenge to characterization. At present, these areas cannot support the same detailed analysis as the rest of the system. Similarly, the bedrock that underlies the mostly unconsolidated VCP aquifer system is only sparsely characterized and must remain outside the scope of this report. By regulatory definition, the bedrock is also excluded from Virginia's groundwater management areas (GWMAs).

Other limitations involve unreported groundwater withdrawals, which are either estimated or absent from the data. In addition, many of the analyses presented below are based on numerical groundwater flow models. These models are calibrated to observational data and have proved extremely useful, but like all models they require estimates and assumptions. Also, at the time when most of the analyses occurred, the most recent available reported withdrawal data were from 2023. Certain sections below also include 2024 data that has since been reported to DEQ.

Finally, this report considers groundwater quality mainly in terms of larger-scale, longer-term ambient conditions as they are influenced by local and regional groundwater extraction—for example, the potential movement of saline groundwater into freshwater aquifers. The relatively local, shallow effects of anthropogenic (human-caused) contamination on groundwater quality are generally beyond the scope of this report, except insofar as regional groundwater extraction may increase the VCP aquifer system's longer-term susceptibility to contamination. These limitations are elaborated in the relevant sections of the report.

1.2 Description of Study Area

1.2.1 Boundaries

The SJ 25 study area east of I-95 generally coincides with the VCP, one of Virginia's five physiographic provinces. This province is part of the larger Atlantic Coastal Plain that stretches from Cape Cod, Massachusetts, and Long Island, New York, to the Gulf Coast ([Fenneman, 1946](#)). The VCP extends from the Piedmont province's eastern boundary, known as the Fall Zone, to the shoreline of the Atlantic Ocean ([Figure 2](#)). The VCP's major hydrographic features include four large estuarine rivers (Potomac, Rappahannock, York, and James), the Chesapeake Bay, and the Great Dismal Swamp. The land surface "is characterized by rolling terrain and deeply incised stream valleys in the northwestern part, and gently rolling-to-level terrain, broad stream valleys, and extensive wetlands in the eastern and southern parts" ([McFarland and Bruce, 2006](#)). The land area east of the Chesapeake Bay, known as Virginia's Eastern Shore, is the southernmost part of the Delmarva Peninsula. The VCP's subsurface consists of an eastward-thickening wedge of mostly unconsolidated sediments that compose the aquifer system described in [Section 1.2.2](#).

The I-95 corridor runs along the east side of the Fall Zone, so that a strip of VCP sediments lies between the two ([Figure 2](#)). Within the strip, VCP sediments form a relatively thin layer, dissected by stream erosion, atop the fractured bedrock of the Piedmont province. These marginal VCP sediments do not support extensive groundwater production, and many water wells in this area target the underlying bedrock instead. For the purposes of the SJ 25 groundwater study and report, this strip is disregarded, and I-95 is treated as the approximate western edge of the VCP aquifer system.

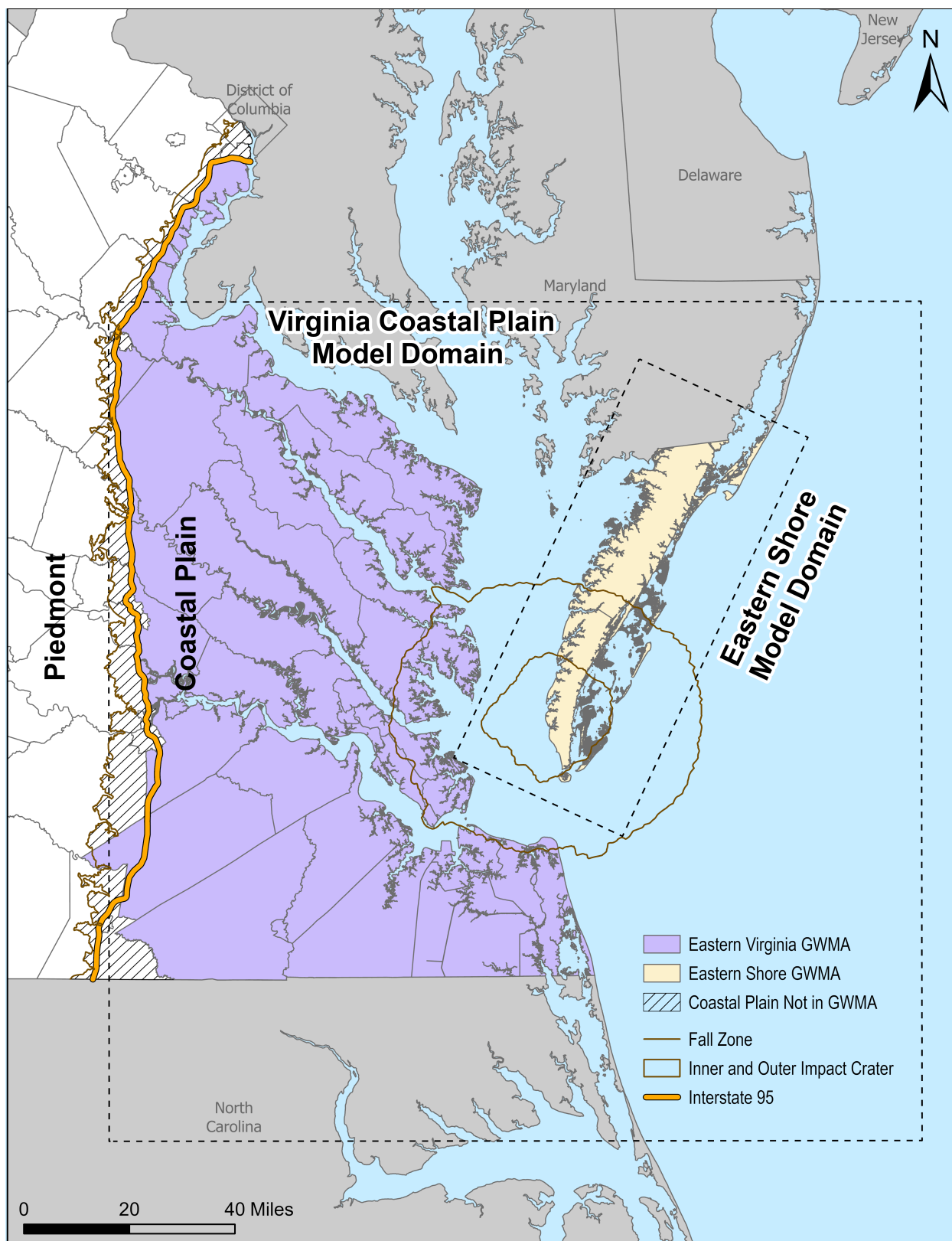


Figure 2: Map of the Virginia Coastal Plain study area east of I-95, including geological features, physiographic boundaries, administrative boundaries, regulatory groundwater management areas (GWMA), and groundwater flow model domains. Refer to text for supporting citations.

Similarly, I-95 generally defines the western edge of the Eastern Virginia GWMA. The Virginia Administrative Code specifies the localities that make up the Eastern Virginia GWMA and the Eastern Shore GWMA². These geographic areas are subject to Virginia’s Groundwater Withdrawal Regulations³. Both GWMA’s are illustrated on Figure 2. The Eastern Virginia GWMA includes a few small areas west of I-95 and excludes a few small areas east of I-95. The portions of the VCP that are located outside the GWMA are indicated by diagonal stripes on Figure 2. These minor divergences between physiographic, administrative, and regulatory boundaries are noted for clarity but do not appreciably affect the results of the analyses reported below.

Many of the analyses were based on established numerical models of groundwater flow (see Section 1.4.4). Each of the two models encompasses a defined spatial domain (Figure 2). The larger VCP model domain was designed so that its western boundary would coincide generally with the Fall Zone. Notably, the northern boundary of the model domain excludes portions of Stafford County, Prince William County, and Fairfax County that are located within both the VCP physiographic province and the Eastern Virginia GWMA. This marginal area was incorporated into the Eastern Virginia GWMA when it expanded on January 1, 2014. However, the area is geologically complex and hydraulically somewhat isolated from the main VCP, and it lacks sufficient historical data for thorough hydrogeological characterization and groundwater flow modeling. It was therefore excluded from detailed analysis, but a preliminary investigation is underway (Section 1.4.5).

The VCP model domain is three-dimensional, extending vertically from the land surface to the bedrock that lies at the base of the unconsolidated VCP sediments. This vertical boundary is consistent with the regulatory declaration of GWMA’s, which states, “All aquifers located between the land surface and basement rock within the geographic area defined will be included in the area”⁴. The Eastern Shore model domain extends from the land surface to the base of the freshwater aquifer system, which lies far above the basement rock in that region (Section 1.4.4).

1.2.2 Virginia Coastal Plain Aquifer System

Key Point #1

The **confined** Potomac aquifer is the largest and deepest in the VCP, accounting for 70% of total reported and estimated groundwater withdrawals in the Eastern Virginia Groundwater Management Area. The confined Yorktown-Eastover aquifer system accounts for 95% of total reported and estimated groundwater withdrawals in the Eastern Shore Groundwater Management Area. **Combining the two regulated areas, the major uses of groundwater are industrial (35% of total), private domestic (34%), and public water supply (26%).** See also Section 1.5.

The sediments of the Atlantic Coastal Plain are subdivided into the Northern Atlantic Coastal Plain aquifer system, one of the nation’s primary aquifer systems. This large system extends from Long Island, New York, to northeastern North Carolina (Figure 3) and includes the regional VCP aquifer system. Most VCP aquifers and **confining units** can be correlated across state lines to equivalent units in Maryland and North Carolina, but some units are present only in Virginia. **Hydrogeologic** units vary laterally, resulting in some different naming conventions in adjacent states. For example, the Chesapeake Bay impact crater (shown in Figure 2 and others) contains sediments that comprise confining units that are only present in Virginia, including the Chickahominy confining unit and the Exmore Matrix and Clast confining units (McFarland and Bruce, 2006). The Chesapeake Bay impact crater and associated sediments have influenced groundwater flow in the VCP aquifer system, resulting in the “inland saltwater wedge” feature of the saltwater-transition zone along the Virginia coast illustrated in Figure 4. The blue arrows in Figure 4 illustrate the generalized present-day groundwater flow paths within the VCP aquifer system.

²See 9 VA. ADMIN CODE 25-600-20.

³See 9 VA. ADMIN CODE 25-610.

⁴See 9 VA. ADMIN CODE 25-600-20.

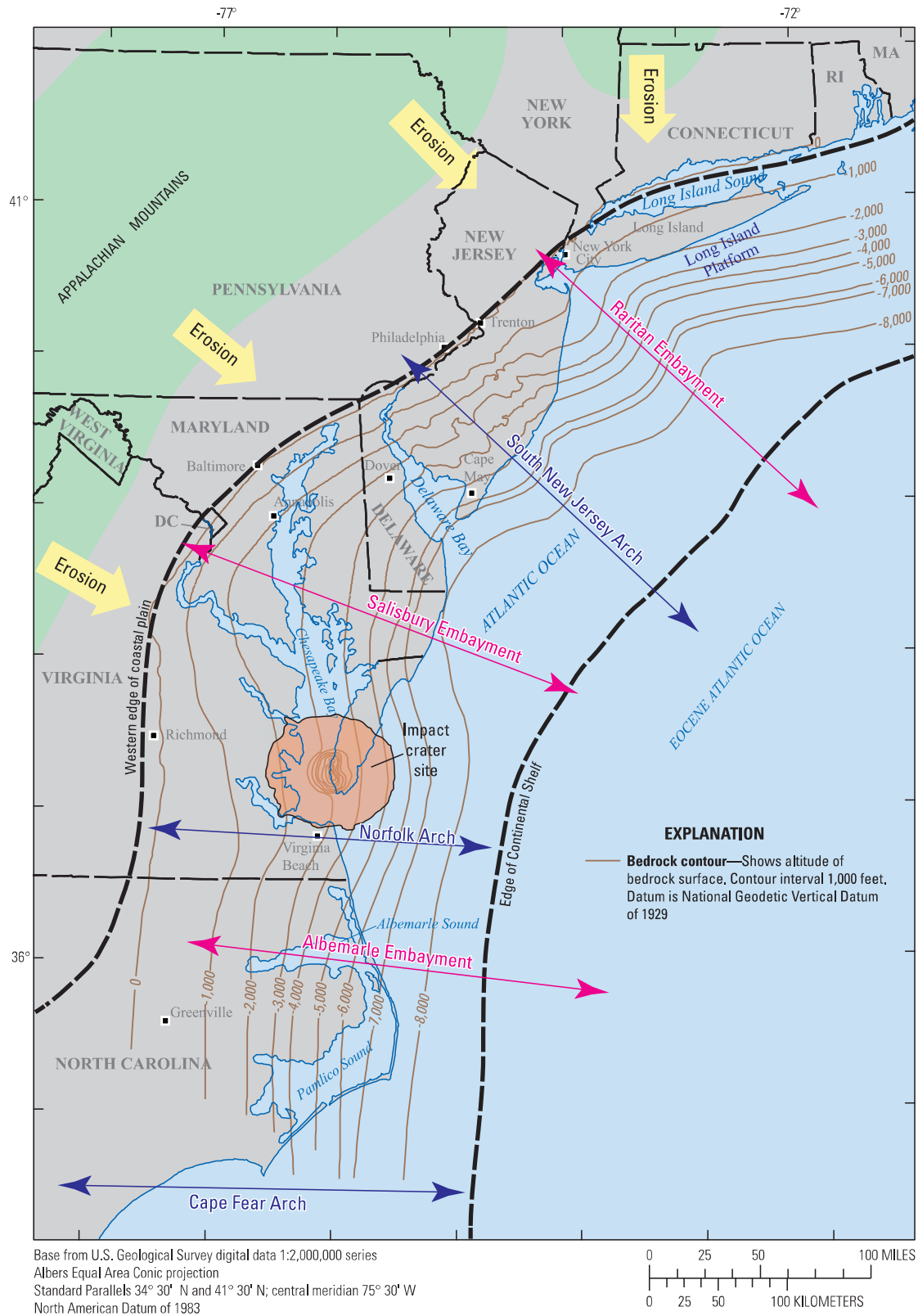


Figure 3: Schematic diagram showing the Northern Atlantic continental margin, the generalized bedrock structures (higher arches and lower embayments) beneath the VCP, and the inferred ancient source regions of sediments that compose the VCP. Reproduced from [Masterson et al. \(2015\)](#).

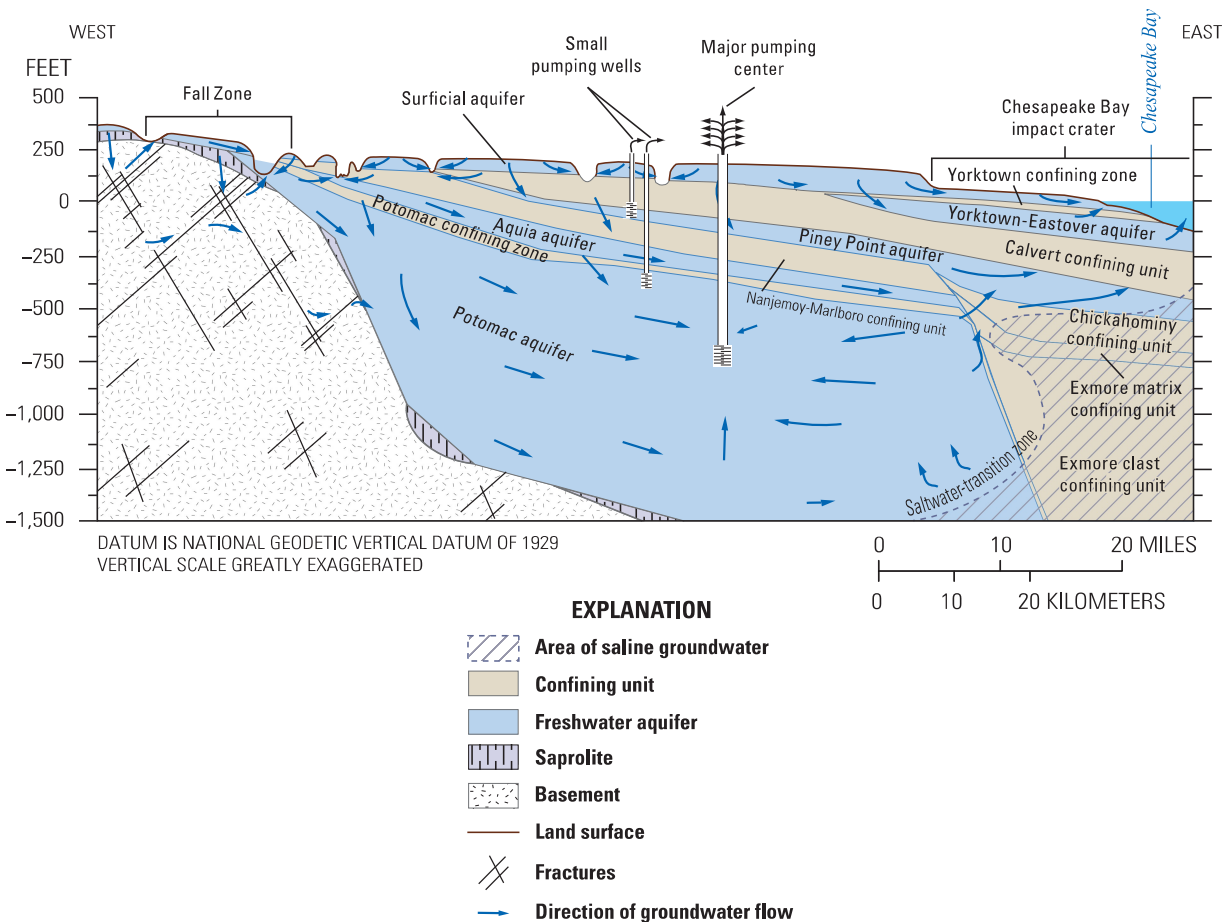


Figure 4: Generalized hydrogeologic section showing principal aquifers, confining units and zones, and conceptual present-day patterns of groundwater flow in the Virginia Coastal Plain west of the Chesapeake Bay. Reproduced from [Kearns and Pope \(2025\)](#).

The VCP aquifer system extends vertically from the land surface to the basement bedrock. Fractured bedrock of the Piedmont physiographic province forms the western boundary of the VCP aquifer system in the Fall Zone and extends eastward beneath the wedge of sediments comprising the VCP aquifer system. The basement bedrock has not been extensively characterized or explored as a potential groundwater source, but its primary structural configuration and depth are well documented at regional scale; see Figure 3.

The bedrock basement underlying the VCP aquifer system south of the James River forms a structural high known as the Norfolk Arch. On the arch's southern flank, the basement bedrock declines into North Carolina, to a structural low known as the Albemarle Embayment. On the arch's northern flank, the basement bedrock declines into Maryland, to an even deeper structural low known as the Salisbury Embayment (Figure 3). As a result, the VCP aquifer system is thinner and shallower over the Norfolk Arch and thicker and deeper on its northern and southern flanks, approaching the embayments.

Figure 5 lists the eight aquifers (shaded in blue) and 11 confining units within the aquifer system of the VCP, and additional details about each hydrogeologic unit are provided in Table 1. The most important, widespread, and most used aquifer in the VCP aquifer system is the confined Potomac aquifer. The Potomac aquifer is fluvial-deltaic in origin, composed primarily of sand and gravel deposited as streams, alluvial fans, and deltas, approximately 100 to 145 million years ago. The **unconfined** surficial aquifer and the Peedee aquifer are also fluvial in origin. The other five aquifers are the result of marine deposition. The marine aquifers were deposited primarily as a combination of shell and sand when the VCP was inundated by the Atlantic Ocean during extended periods of elevated sea level, which occurred multiple times during the past 59 million years. Each time the sea level rose and the ocean inundated the VCP, the sediments filled with salty

water as the saltwater-transition zone migrated westward (Figure 4). When the sea level fell and the ocean receded, the sediments were recharged with fresh water from precipitation, driving the saltwater-transition zone eastward in a process known as groundwater flushing (Sanford, 1913).

Figure 5 also illustrates the groupings of hydrogeologic units that were used in the groundwater budget analysis that is presented later in this report (Section 2.4.3). The surficial aquifer and the Potomac aquifer were individually analyzed in the groundwater budget analysis, while the intervening hydrogeologic units were considered as a group. This method was selected because the surficial aquifer is the primary route of entry for precipitation into the VCP aquifer system and because the Potomac aquifer is the largest source of groundwater withdrawals from the VCP aquifer system. The intervening hydrogeologic units were grouped to simplify the overall analysis, but each unit has distinct characteristics that are relevant to other considerations (Table 1).

The VCP aquifer system extends beneath the Virginia Eastern Shore. However, in this area, groundwater deeper than the Yorktown-Eastover aquifers is too saline for domestic use or public water supply without pretreatment. Fresh groundwater on the Eastern Shore is obtained from either the **unconfined** surficial aquifer or the **confined** Yorktown-Eastover aquifer system, which is composed of an upper, middle, and lower aquifer (Figure 6a). A recent study by McFarland and Beach (2019) has identified three buried **paleochannels** that traverse and incise the Eastern Shore, each of which contains an upper and lower confined aquifer that intersects the Yorktown-Eastover aquifer system and either restricts or facilitates groundwater flow, depending on the locations and depths of the intersections and which hydrogeologic units are in contact (Figure 6b).

The groundwater flow on the Eastern Shore is generally downward and away from the relatively higher elevation central ridge on the Eastern Shore (blue arrows in Figure 6c), either to discharge into surface waters or to infiltrate downward into the underlying hydrogeologic units. Once groundwater enters the underlying hydrogeologic units, it eventually moves outward and upward toward the Chesapeake Bay and the Atlantic Ocean, due to the freshwater/saltwater interface denoted by the pink boundary line in Figure 6c.

Figures 2, 3, and 4 illustrate the position of the inner and outer rims of the Chesapeake Bay impact crater. This feature, approximately 53 miles in diameter, formed when an impactor struck the earth during the late Eocene epoch approximately 35 million years ago. This event vaporized and removed the rock and sediment within the inner rim to approximately 5,000 feet below current sea level, and within the outer

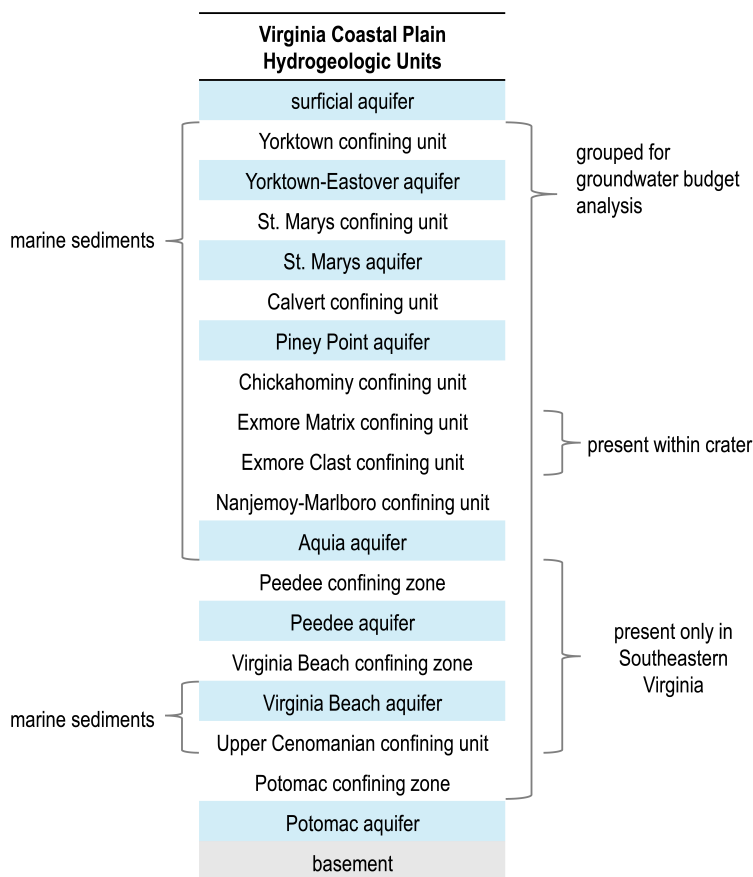


Figure 5: Simplified stratigraphic relations among hydrogeologic units of the Virginia Coastal Plain. Adapted from McFarland and Bruce (2006) and McFarland (2013). Associations among some hydrogeologic units that cross stratigraphic boundaries are not shown. Aquifers, shown in blue, are described in Table 1. The sedimentary units other than the surficial aquifer and the Potomac aquifer were grouped for the purpose of the regional groundwater budget analysis presented in Section 2.4, below.

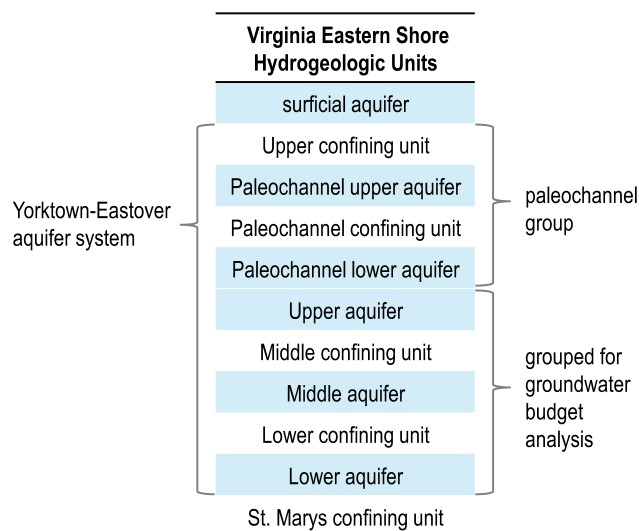
rim to a depth between approximately 1,000 and 3,000 feet depending on location. This impact and the re-deposition of materials into the crater it formed resulted in a feature of the VCP aquifer system known as the inland saltwater wedge, which was recognized by [Sanford \(1913\)](#) almost 90 years before the crater itself was discovered ([McFarland and Bruce, 2005](#)).

Table 1: List of VCP aquifers and condensed descriptions, in order of increasing depth. Modified from [Kearns and Pope \(2025\)](#). The aquifers are separated by confining units and zones not described here; detailed in [McFarland and Bruce \(2006\)](#).

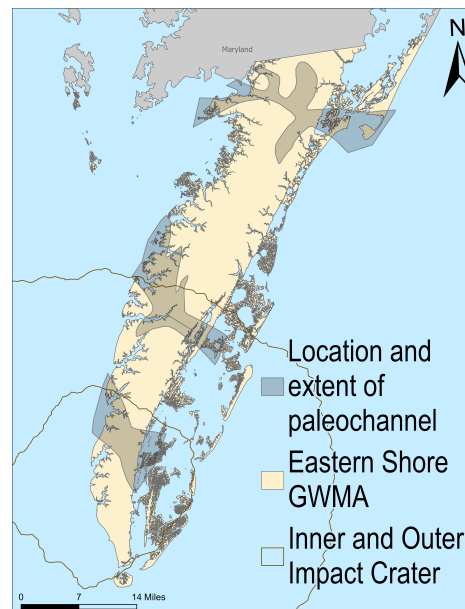
Aquifer	Description
surficial aquifer	Unconfined water-table aquifer, sometimes known informally as the “Columbia” aquifer, that covers the entire Virginia Coastal Plain at a variable thickness up to many tens of feet. Comprises a series of primarily fluvial-deltaic and estuarine quartz sands and gravels of variable texture with interbedded silts and clays (McFarland and Bruce, 2006). Mostly overlies various confining units or zones but locally in contact with deeper aquifers. Historically an important source for water supply, but less so recently because of drought and decreasing water quality (Pope et al., 2008).
Yorktown-Eastover aquifer	Extends across most of the VCP except for several northwestern counties. Upper part composed of estuarine to marine, variably textured, glauconitic, phosphatic, and fossiliferous quartz sands and interbedded silts and clays; lower part composed of abundantly fossiliferous sands (McFarland and Bruce, 2006). Hydraulically continuous on a regional scale, with local discontinuities from interbedded fine-grained sediments. Shallow aquifer with high-quality water; a major source for private-domestic water supplies, especially in the eastern part of the Virginia Coastal Plain (Pope et al., 2008). On the Eastern Shore, the “Yorktown-Eastover aquifer system” comprises separate upper, middle, and lower confined aquifers separated by confining units (Sanford et al., 2009a ; McFarland and Beach, 2019). See Figure 6. Sediments in buried paleochannels that cut through this system were recently designated as upper and lower paleochannel aquifers separated by a confining unit (McFarland and Beach, 2019). The U.S. Environmental Protection Agency (EPA) has designated the “Columbia and Yorktown-Eastover Multiaquifer System” a sole source aquifer (62 FR 17187[1997]) under Section 1424(e) of the Safe Drinking Water Act, 42 U.S.C., section 300h-3(e).
St. Marys aquifer	Limited regional extent. Northern part composed of Miocene marine sands and shells ranging in thickness from 150 to 200 ft, covering most of the Virginia Eastern Shore, containing brackish water (McFarland and Bruce, 2006). Southern part, mostly in the City of Suffolk, includes a coarse-grained basal deposit of silty, glauconitic, phosphatic, and micaceous quartz sands and fossil shells approximately 50 ft thick (McFarland and Bruce, 2006); a marginal water-production aquifer (Pope et al., 2008).

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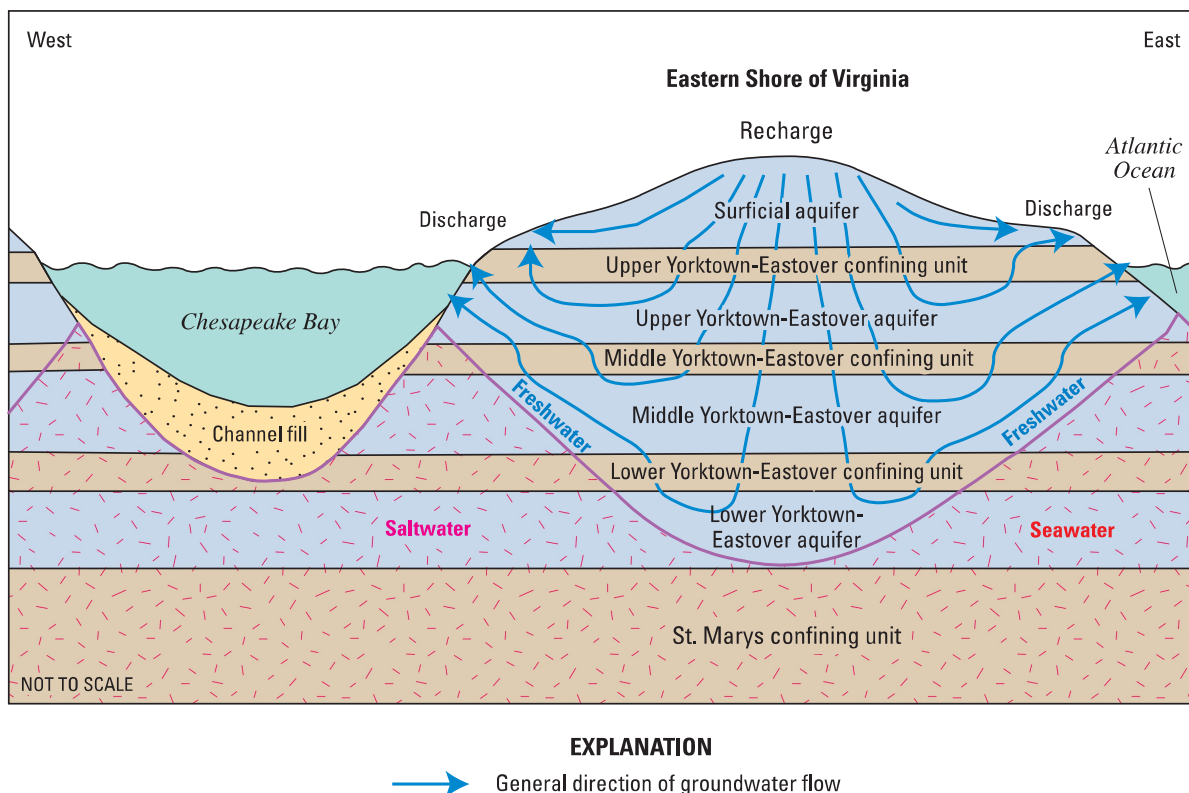
Aquifer	Description
Piney Point aquifer	Extends across most of the Virginia Coastal Plain, except in the southern part near the Fall Zone. Comprises several geologic formations, consisting generally of marine, medium- to coarse-grained, glauconitic, phosphatic, variably calcified, and fossiliferous quartz sands up to 150 ft thick (McFarland and Bruce, 2006). A moderately used groundwater resource in the central sections of the Northern Neck Peninsula, Middle Peninsula, and York-James Peninsula, where withdrawals are primarily from a section of the aquifer identified as consolidated limestone by McFarland (2017) ; not considered a productive aquifer south of the James River (Pope et al., 2008).
Aquia aquifer	Extends across much of the VCP, except for the Eastern Shore, the Chesapeake Bay impact crater, and the southern area of the Fall Zone. Composed of marine, medium- to coarse-grained, glauconitic, and fossiliferous quartz sands; generally no more than 50 ft thick (McFarland and Bruce, 2006). A minor water-supply resource, possibly because of its thinness relative to other aquifers; used mostly in the northern and central part of the Virginia Coastal Plain (Pope et al., 2008).
Peedee aquifer	Extent limited to the southern parts of the Cities of Chesapeake and Virginia Beach; never more than several tens of feet thick. Composed of discontinuous fine-grained sediments interbedded with coarse-grained sediments that overlie the Virginia Beach confining zone. Possibly of local importance for groundwater flow, but unused as a source of groundwater in Virginia (McFarland and Bruce, 2006).
Virginia Beach aquifer	Extends across most of Virginia Beach, westward across Chesapeake and Suffolk, and into the southeastern corner of Southampton County. Consists of primarily fluvial-deltaic and variably textured quartz sands and gravels attaining thicknesses up to 70 ft (McFarland and Bruce, 2006). A hydraulically continuous unit, providing water supply mostly in the City of Suffolk (Pope et al., 2008).
Potomac aquifer	The largest, deepest, and most heavily used source of groundwater in the VCP (McFarland and Bruce, 2006). Extends across nearly the entire VCP, except for the inner part of the Chesapeake Bay impact crater. Thickens from a feather edge near the Fall Zone to several thousand feet at the coastal margin. Occupies the lowest stratigraphic position in the VCP aquifer system, directly atop basement bedrock. Composed primarily of fluvial-deltaic coarse-grained quartz and feldspar sands and gravels interbedded with clays (McFarland and Bruce, 2006); distribution of these sediment types varies regionally with structural features (McFarland, 2013). Overlain by the Potomac confining zone across most of its extent, except for incised areas along major river channels and near the Fall Zone where it may outcrop but is usually covered by sediments of the surficial aquifer, possibly providing direct hydraulic connections between the confined and unconfined systems (Pope et al., 2008). Hydraulically continuous on a regional scale, but compositional heterogeneity may impede groundwater flow locally (Pope et al., 2008).



(a) Simplified stratigraphic relations among hydrogeologic units of the Virginia Eastern Shore (adapted from [McFarland and Beach, 2019](#), and [McFarland, 2019](#)). Associations among some hydrogeologic units that cross stratigraphic boundaries are not shown. Aquifers, shown in blue, are described in Table 1. The units from the Upper Yorktown-Eastover aquifer to the Lower Yorktown-Eastover aquifer were grouped for the purpose of the regional groundwater budget analysis presented in Section 2.4, below.



(b) Location and extent of buried paleochannels on the Eastern Shore (recreated from [McFarland and Beach, 2019](#), and [McFarland, 2019](#)).



(c) Generalized hydrogeologic section showing principal aquifers, confining units, and conceptual patterns of groundwater flow in the Virginia Eastern Shore aquifer system. Paleochannel units not shown. Reproduced from [Sanford et al. \(2009a\)](#).

Figure 6: Virginia Eastern Shore hydrogeology.

1.3 Regulatory Background and Framework

Groundwater withdrawals in the study area are regulated by the Ground Water Management Act of 1992. An understanding of the Ground Water Management Act of 1992, and the regulatory history that led to its enactment, is necessary to understand the findings in this report as well as the assessment of the regulatory effectiveness of the Ground Water Management Act of 1992 required by SJ 25. This section reviews the development of groundwater management in Virginia from the largely unregulated common-law era, to the General Assembly's first attempt at statutory controls with the Groundwater Act of 1973, to the present-day Ground Water Management Act of 1992.

1.3.1 Pre-Statutory Era

For the majority of its tenure as a Commonwealth, Virginia's groundwater was almost entirely unregulated. Until 1973, there were no codified laws or regulations concerning groundwater withdrawals in the Commonwealth. Groundwater was controlled only by judicial appeals to the common law. Common law was not (and still is not)⁵ a comprehensive framework through which groundwater supply and groundwater quality could be managed.⁶

Under the common law, injured parties could seek redress in court. This retroactive, dispute-focused approach made groundwater use and planning impossible from a regulatory perspective. Further, common law in Virginia relied on what is known as the "English rule."⁷ This meant that landowners held a nearly absolute right to the use of water under the surface of their property and had no obligation to consider how this use might affect others.⁸ Common law, then, was not a basis on which a groundwater management framework could be built.

1.3.2 Beginning of the Statutory Era: The Groundwater Act of 1973

Until 1973, groundwater use in Virginia was limited only by common law, and then only loosely.⁹ Cognizant of declining groundwater resources, particularly in the VCP, the General Assembly enacted the Groundwater Act of 1973.¹⁰ The Groundwater Act of 1973's stated purpose was to:

recognize and declare that the right to reasonable control of all groundwater resources within this State belongs to the public and that in order to conserve, protect and beneficially utilize the ground-water of this State and to ensure the preservation of the public welfare, safety and health, it is essential that provision be made for control of groundwater resources.¹¹

In essence, then, the Groundwater Act of 1973 was meant to provide for the "control of groundwater resources." Further, according to the 1973 Virginia General Assembly this control should be used to "conserve, protect and . . . utilize" groundwater for the public benefit.

The mechanism by which the Groundwater Act of 1973 was intended to achieve these goals was by limiting groundwater use in management areas to "the extent [of a permitted user's] beneficial uses thereof on the date such area is declared a critical groundwater area or on any date within two years prior to such date."¹² This amount of groundwater was recorded in a certificate of groundwater right issued by the State Water Control Board. Individuals or entities who used less than 50,000 gallons per day (gal/day), or were

⁵ See VA. CODE ANN. § 1-200. This section of the Code of Virginia provides that the common law of England still applies, so long "as it is not repugnant to the principles of the [Virginia] Bill of Rights and the Constitution of this Commonwealth . . . except as altered by the General Assembly."

⁶ See generally George A. Somerville, *Common Law Groundwater Rights Under Virginia Law*, 34 Va. Env'tl. L.J. 204 (2016) (offering a comprehensive review of the attempts to use common law to regulate groundwater in Virginia).

⁷ See *Id.* at 206.

⁸ See *Id.* Note, however, common law does consider water in "underground streams" a public resource that should not be used with such abandon. These streams are few and far between, if they even exist at all in Virginia. See *Id.* at 207-9.

⁹ See *Id.*

¹⁰ VA. Acts of Assembly 1973, Ch. 443, 672-681.

¹¹ *Id.* at 673.

¹² *Id.* at 675.

otherwise excluded by the Groundwater Act of 1973, did not need to apply for a certificate of groundwater right.¹³

Individuals or entities that sought to “acquire or enlarge” a groundwater withdrawal within critical groundwater areas were required to obtain a permit to do so, unless excluded by the Groundwater Act of 1973.¹⁴ These permits were issued by the State Water Control Board pursuant to an application process described in the Groundwater Act of 1973.

The Groundwater Act of 1973 allowed for expansive groundwater use even within management areas, reaching 220 Mgal/day of permitted withdrawals at its peak. This upper limit was likely never utilized, but if it had been, the VCP system would have been unable to sustain it. Ultimately, studies conducted at the direction of the State Water Control Board indicated that the coastal plain aquifers were oversubscribed and were at risk of severe **dewatering**. These findings led the General Assembly to repeal the Groundwater Act of 1973 and replace it with the Ground Water Management Act of 1992.

1.3.3 The Modern Regulatory Era: The Ground Water Management Act of 1992

After nearly two decades under the Groundwater Act of 1973 framework, the General Assembly replaced its original groundwater management legislation with the Ground Water Management Act of 1992. The Ground Water Management Act of 1992’s stated goals are much the same as its predecessor; the Ground Water Management Act of 1992 is also primarily concerned with responsible “control of groundwater resources” for the benefit of the public. In fact, the Ground Water Management Act of 1992’s “Purpose” section is nearly identical to that of the Groundwater Act of 1973.¹⁵

The only substantive change made to the “Purpose” section in the Ground Water Management Act of 1992 was an acknowledgment of the need to improve upon the Groundwater Act of 1973’s inability to prevent groundwater depletion and pollution. The Ground Water Management Act of 1992 notes that “pursuant to the Groundwater Act of 1973, the continued, unrestricted usage of ground water is contributing and will continue to pollution and shortage of ground water, thereby jeopardizing the public welfare, safety and health.”¹⁶ It is worth noting that the General Assembly saw fit to explicitly note the former statute’s shortcomings, as it confirms the Groundwater Act of 1973’s repeal and replacement was more than a simple modernizing refreshment. Instead, the General Assembly signaled that it thought the Groundwater Act of 1973 was insufficient to protect groundwater resources. Consequently, the differences between the two acts are telling when analyzing exactly what issues the General Assembly meant to remedy with the Ground Water Management Act of 1992 and, in turn, the goals of the Commonwealth’s current groundwater management law.

One of the more impactful changes included in the Ground Water Management Act of 1992 was the expansion of the class of covered users. Where the Groundwater Act of 1973 largely only applied to non-agricultural “industrial or commercial” users, the Ground Water Management Act of 1992 applies to a much broader class of users. The Groundwater Act of 1973 carved out, among other groups, agricultural users, allowing them to withdraw without a permit in management areas. After the Ground Water Management Act of 1992 took effect, agricultural withdrawers were required to apply for a permit based on the same standards as other covered users.

Accompanying this expansion of the types of users required to obtain a permit, the Ground Water Management Act of 1992 shifted from limiting groundwater use to the extent of a beneficial use on a given day to the minimum withdrawal necessary for a proposed beneficial use.¹⁷ Existing users at the time the Ground Water Management Act of 1992 went into effect were evaluated based on annual, rather than daily use, more accurately reflecting actual need. Further, these existing users were required to obtain permits, and certificates of groundwater rights were eventually phased out. The Ground Water Management Act of

¹³*Id.* at 674 (“No certificate of groundwater right, permit or registration statement authorized by this Act shall be required for the use or supplying of groundwater for agricultural and livestock watering purposes, for human consumption or domestic purposes, or for any single industrial or commercial purpose in an amount not exceeding fifty thousand gallons a day.”)

¹⁴*Id.*

¹⁵VA. CODE ANN. § 62.1-254.

¹⁶*Id.*

¹⁷For an in-depth discussion of what constitutes a “beneficial use,” see the VA. DEPT. OF ENV’T. QUALITY, A REPORT TO THE HOUSE AGRICULTURE, CHESAPEAKE AND NATURAL RESOURCES COMMITTEE: HB 1186: SUMMARY OF STAKEHOLDER ENGAGEMENT AND THE VIRGINIA DEPARTMENT OF ENVIRONMENTAL QUALITY’S INTERPRETATION OF ITEMS 1–3 OF § 62.1-44.36 OF THE CODE OF VIRGINIA (2018).

1992 also reduced the volume-based exclusion threshold to 300,000 gallons in any one month, about 1,200,000 gallons less than the analogous provision in the Groundwater Act of 1973.¹⁸

The Ground Water Management Act of 1992 applied a more rigorous standard to a broader class of users than the Groundwater Act of 1973 in an attempt to control for some of the Groundwater Act of 1973's identified shortcomings. The State Water Control Board has promulgated a robust framework of regulations to make the Ground Water Management Act of 1992's statutory provisions actionable. The interaction between the current statute and the regulations is described in the section below.

1.3.4 The Current Statutory and Regulatory Framework

The Ground Water Management Act of 1992 provides a framework through which DEQ can regulate and monitor the use of groundwater in declared GWMA's.¹⁹

The Ground Water Management Act of 1992 outlines the process for the State Water Control Board to establish a GWMA in regulation.²⁰ The first step is the State Water Control Board has to initiate a groundwater management proceeding, based either upon its own motion or in response to a petition from a county, city, or town. Initiating a groundwater management proceeding requires the State Water Control Board to make a judgment that there may be reason to believe that one or more of the following conditions exist:

1. Groundwater levels in the area are declining or are expected to decline excessively;
2. The wells of two or more groundwater users within the area are interfering or may reasonably be expected to interfere substantially with one another;
3. The available groundwater supply has been or may be overdrawn; or
4. The groundwater in the area has been or may become polluted. Such pollution includes any alteration of the physical, chemical or biological properties of ground water which has a harmful or detrimental effect on the quality or quantity of such waters.

If the State Water Control Board finds that any one of these conditions exist, and further finds that the public welfare, safety, and health require regulatory efforts, then the State Water Control Board, through a regulatory action, declares the area to be a GWMA.

Currently there are two declared GWMA's in the Commonwealth, the Eastern Virginia GWMA and the Eastern Shore GWMA.²¹ Collectively, these two areas cover most of the Commonwealth east of I-95.²² These two GWMA's are in the Coastal Plain where there have been longstanding and documented concerns about depletion of groundwater, land **subsidence**, and saltwater **intrusion**.

Generally speaking, the key distinction between a GWMA and other areas of the Commonwealth is that in a GWMA a groundwater withdrawal permit is required to withdraw 300,000 gallons or more in any one month, unless otherwise excepted by the Ground Water Management Act of 1992 or regulations.²³ For a frame of reference, 300,000 gallons is roughly the amount of water used by a 30-home subdivision in a month. Groundwater withdrawals outside of a GWMA are not subject to DEQ groundwater withdrawal permitting requirements.

Given the location of the two declared GWMA's, in essence, any individual or entity that is not exempt from the provisions of the Ground Water Management Act of 1992 must first seek a permit from DEQ to

¹⁸Note that the Ground Water Management Act of 1992 also introduced a monthly standard in contrast to the Groundwater Act of 1973's daily standard.

¹⁹Although the text of the Ground Water Management Act of 1992 references the State Water Control Board as the acting regulatory body, as of 2022, the State Water Control Board no longer has permitting authority. Therefore, any references in the text of the Act to the State Water Control Board's permitting authority should instead be interpreted to describe DEQ's permitting authority. See VA. CODE ANN § 62.1-255 ("‘Board’ means the State Water Control Board. However, when used outside the context of the promulgation of regulations, including regulations to establish general permits, pursuant to this chapter, ‘Board’ means the Department of Environmental Quality.")

²⁰VA. CODE ANN. § 62.1-257.

²¹9 VA. ADMIN CODE § 25-60-20.

²²*Id.*

²³See VA. CODE ANN. §§ 62.1-258 and 62.1-259.

withdraw groundwater from the VCP system. These permits are subject to certain conditions,²⁴ namely, that they must be for a “beneficial use” and only for the amount required for that proposed beneficial use.²⁵ Additionally, the permit must include a water conservation and management plan (WCMP). A WCMP sets out procedures by which the permittee will ensure it uses the least amount of groundwater necessary and minimizes waste.

There are also exceptions to the permit requirements. Any of the following withdrawals do not require a groundwater withdrawal permit²⁶:

1. Withdrawals of less than 300,000 gallons per month;
2. Temporary construction dewatering;
3. Temporary withdrawals associated with a state-approved ground water remediation;
4. Withdrawal of groundwater for use by a groundwater heat pump where the discharge is reinjected into the aquifer from which it is withdrawn;
5. Withdrawal from a pond recharged by groundwater without mechanical assistance;
6. Withdrawal of water for geophysical investigations, including pump tests;
7. Withdrawal of groundwater coincident with exploration for and extraction of coal or activities associated with coal mining regulated by the Department of Energy;
8. Withdrawal of groundwater coincident with the exploration for or production of oil, gas or other minerals other than coal, unless such withdrawal adversely impacts aquifer quantity or quality or other ground water users within a ground water management area; or
9. Withdrawal of ground water pursuant to a special exception issued by the State Water Control Board.

It is important to note, however, that these exceptions are only relevant within GWMA. Withdrawals outside of GWMA do not require a groundwater withdrawal permit regardless of their magnitude or character. In addition, withdrawal of groundwater discharged from free flowing springs where the natural flow of the spring has not been increased by any method is excluded from permitting by the Groundwater Withdrawal Regulations.²⁷

Although not subject to permitting requirements, individuals or entities withdrawing groundwater for any purpose outside of a GWMA are still required to furnish DEQ with information concerning those withdrawals upon request. Nonagricultural withdrawers outside of GWMA who withdraw more than 10,000 gal/day of groundwater are required to report their withdrawals to DEQ on an annual basis. Agricultural withdrawers who withdraw 1,000,000 gallons per month or more are also required to submit annual withdrawal reports. Permitted withdrawers report withdrawal data more frequently, these reports are due on a quarterly basis.

The Ground Water Management Act of 1992 introduced a need-based analysis to DEQ’s groundwater withdrawal permit review by requiring DEQ to “ensure that the maximum possible safe supply of ground water will be preserved and protected for all other beneficial uses.”²⁸ To effectuate this provision, DEQ regulations limit permitted withdrawals to the amount required for the permitted use.²⁹ Consequently, permit applicants must demonstrate need as part of the approval process. DEQ considers three main factors when conducting the analysis of need:

²⁴The Ground Water Management Act of 1992 instructs DEQ to consider several factors when making permit determinations. See VA. CODE ANN. § 62.1-263. (“When reviewing an application for a permit to withdraw ground water, or an amendment to a permit, the Board may consider the nature of the proposed beneficial use, the proposed use of alternate or innovative approaches such as aquifer storage and recovery systems and surface and ground water conjunctive uses, climatic cycles, unique requirements for nuclear power stations, economic cycles, population projections, the status of land use and other necessary approvals, and the adoption and implementation of the applicant’s water conservation and management plan.”)

²⁵VA. CODE ANN. § 62.1-263. (“In no case shall a permit be issued for more ground water than can be applied to the proposed beneficial use.”)

²⁶VA. CODE ANN. § 62.1-259.

²⁷9 VA. ADMIN CODE § 25-610-50 11.

²⁸VA. CODE ANN. § 62.1-263.

²⁹9 VA. ADMIN CODE § 25-610-40 B (“No permit or special exception shall be issued for more groundwater than can be applied to the proposed beneficial use.”)

1. Whether the applied for withdrawal actually serves an existing or reasonably certain future beneficial use (i.e. a new industrial plant requiring water for its operation);
2. How much water does the identified need require; and
3. Whether anything in the proposed use could contribute to efficiency gains or water losses, altering the total withdrawal amount required for the identified need.

In addition to these three factors, DEQ evaluates whether there are any alternative water sources available.³⁰ This process requires the applicant to demonstrate that it has considered all practicable water source alternatives to the proposed source. This could mean consideration of surface water or simply an alternative aquifer or well design to minimize groundwater impacts. Public water supply projects are subject to additional alternative source analysis criteria and evaluation by DEQ.³¹

The Ground Water Management Act of 1992 also requires all permit applications for new withdrawals (or those treated as such)³² to include a WCMP.³³ WCMPs describe the applicant's proposed methods of minimizing waste and maximizing water use efficiency. An applicant's WCMP must be consistent with local and regional water supply plans.³⁴ The requirements for WCMPs differ according to use type.³⁵ There are three use types defined in the regulation: 1) Public Water Supply, 2) Commercial and Industrial, and 3) Agricultural.³⁶ Each of these uses has its own specific criteria, but they share at least seven general criteria³⁷:

1. Water Savings Equipment and Processes;
2. Water Loss Reduction Program;
3. Water Use Education Programs;
4. Evaluation of Potential Water Reuse Options;
5. Voluntary Water Use Reductions during Drought or Water Use Emergencies;
6. Required Water Use Restrictions during Drought or Water Use Emergencies; and
7. Penalties for Failure to Comply with Mandatory Water Use Restrictions.

These seven general criteria do not apply in every case to each water use type, but each may be applied in the course of DEQ's case-by-case review of each permit application.

DEQ's regulations require any applications for new withdrawals or expansions or renewals of existing withdrawals to undergo a technical evaluation.³⁸ The technical evaluation relies on modeling the proposed withdrawal. The main intent of the evaluation is to determine if "the maximum safe supply of groundwater will be preserved and protected for all other beneficial uses and that the applicant's proposed withdrawal will have no significant unmitigated impact on existing groundwater users or the groundwater resource."³⁹

DEQ must also evaluate "the areas of any aquifers that will experience at least one foot of water level declines[, if any]" and, optionally, any potential saltwater intrusion that would occur from the proposed withdrawal.⁴⁰ More specifically, the evaluation must conclude that the impacts of the withdrawal will not impact existing withdrawers outside of the applicant's own property.⁴¹ If the evaluation shows that the

³⁰9 VA. ADMIN CODE § 25-610-102 C.

³¹9 VA. ADMIN CODE § 25-610-102 D.

³²See 9 VA. ADMIN CODE 25-610-110 F 1.

³³See VA. CODE ANN. § 62.1-262.

³⁴9 VA. ADMIN CODE 25-610-100 B.

³⁵See *Id.*

³⁶See *Id.*

³⁷See *Id.*

³⁸9 VA. ADMIN CODE § 25-610-110 D.

³⁹9 VA. ADMIN CODE § 25-610-110 D 3.

⁴⁰9 VA. ADMIN CODE § 25-610-110 D 2.

⁴¹9 VA. ADMIN CODE § 25-610-110 D 3 g.

proposed withdrawal's impact will extend beyond the applicant's property, the applicant must generate a mitigation plan detailing how it will minimize and mitigate those impacts.⁴²

The technical evaluation must also show that the proposed withdrawal will not lower water levels in any confined aquifer beyond a specific point.⁴³ Specifically, the evaluation must show "the stabilized effects from the proposed withdrawal in combination with the stabilized combined effects of all existing lawful withdrawals will not lower water levels, in any confined aquifer that the withdrawal impacts, below a point that represents 80% of the distance between the land surface and the top of the aquifer."⁴⁴ The technical evaluation must also show that the proposed withdrawal will not degrade water quality through saltwater intrusion or other means such that it negatively impacts existing other groundwater users.⁴⁵

Certain withdrawals proposed by a subdivision (as defined in Section 15.2-2201 of the Code of Virginia) are required to undergo a technical evaluation prior to approval despite being otherwise exempt from the Ground Water Management Act 1992.⁴⁶ This only applies to subdivisions with "30 or more lots within the subdivision served by private wells."⁴⁷ Prior to subdivision plat approval, the developer must apply for, and DEQ must provide, a technical evaluation of the groundwater supply and hydrology in the area surrounding the proposed development. At the conclusion of the technical evaluation, DEQ must provide a non-binding recommendation as to how the developer might "minimize unmitigated impacts to ground water resources and any offsite impacts to existing ground water users."⁴⁸ As the recommendation is non-binding, the developer need not follow it, but the developer must submit an approved mitigation plan to DEQ for each well not constructed in line with DEQ's recommendation. DEQ also does not have the authority to deny these withdrawals, as they are not required to obtain a permit. There is no requirement for a technical evaluation if all the proposed wells will withdraw from the surficial aquifer. DEQ is authorized to charge the developer up to \$5,000.00 for the technical evaluation.

The cumulative impacts of new subdivisions and private domestic wells are only accounted for retrospectively when their withdrawals affect groundwater levels. There currently is no mechanism for localities to consider the long-term ability of the groundwater resource to supply planned growth.

In addition to the conditions that apply to individual permits, the Ground Water Management Act of 1992 provides that the entire groundwater management framework be administered in a way that prioritizes human consumption.⁴⁹

All of the forgoing come together to create Virginia's current groundwater management framework. The following sections will discuss groundwater trends and findings from DEQ's study with USGS to ultimately evaluate the effectiveness of this framework and its foundation, the Ground Water Management Act of 1992.

1.4 Cooperative Scientific Investigations

Geological studies of groundwater in the VCP began with the U.S. Army's occupation of Fort Monroe during the Civil War, when attempts to drill a drinking water supply well encountered only saltwater. That drilling began in 1864 and continued until 1869, reaching a depth of 907 feet below land surface (BLS). The Army requested that Virginia's State Geologist William Barton Rogers examine the **drill cuttings** to help determine why no fresh groundwater was encountered (Sanford, 1913). These events initiated groundwater exploration and research in eastern Virginia. Most of the early studies that followed were conducted by state agencies, primarily to support economic development in the early 1900s. Later, USGS began to carry out more intensive research, as industrialization and population spiked in Hampton Roads to support the war efforts during World War I and World War II.

The middle and later decades of the 20th century saw rising awareness of the historical groundwater-level declines described elsewhere in this report. These issues led to increased groundwater study and increased monitoring of groundwater levels to improve understanding of the VCP aquifer system. These

⁴² *Id.*

⁴³ VA. ADMIN CODE § 25-610-110 D 3 h.

⁴⁴ *Id.*

⁴⁵ VA. ADMIN CODE § 25-610-110 D 3 i.

⁴⁶ VA. CODE ANN. § 62.1-259.1.

⁴⁷ *Id.*

⁴⁸ *Id.*

⁴⁹ See VA. CODE ANN. § 62.1-263. "When proposed uses of ground water are in conflict or when available supplies of ground water are insufficient for all who desire to use them, preference shall be given to uses for human consumption, over all others."

efforts ultimately yielded a hydrogeologic framework specific to the VCP (Meng and Harsh, 1988). The framework, in turn, enabled the development of a computer groundwater model (Harsh and Lacznik, 1990) that DEQ used for many years in regulating groundwater withdrawals in the Eastern Virginia GWMA.

Since then, most regional-scale groundwater studies in the VCP have been conducted cooperatively by DEQ and USGS. From the late 1980s into the early 2000s, cooperative drilling efforts led to the discovery of the Chesapeake Bay impact crater and provided a plethora of new geological and hydrogeological information that culminated in a new, comprehensive hydrogeologic framework of the VCP in 2006 (McFarland and Bruce), followed by a new groundwater model based on that framework in 2009 (Heywood and Pope). Since 2006, multiple follow-up studies have been published to expand on individual components of the hydrogeologic framework. The 2006 framework and subsequent reports describe and cite earlier studies in detail. This report presents only a summary of the current overall conceptual framework for the VCP that dates back about three decades, to the research that became the 2006 hydrogeologic framework. The sections below summarize previous studies and their significant findings, in several major categories: hydrogeologic frameworks, groundwater quality, domestic groundwater use, and groundwater flow models.

1.4.1 Hydrogeologic Frameworks

Hydrogeologic frameworks define the distribution of aquifers and confining units that underlie a mapped area, controlling the occurrence and movement of groundwater with their geological characteristics and relationships. The publications summarized below have defined and elaborated the hydrogeologic framework that is the basis for current understanding of the VCP aquifer system. These publications also provided the information describing the study area, presented above.

The Regional Aquifer-System Analysis program was created in 1978 by a congressional directive to develop quantitative appraisals of the major groundwater systems of the United States. A product of this program was the defined hydrogeologic framework of Meng and Harsh (1988). This framework built on a wealth of information previously published throughout the early and middle 20th century. For a summary of earlier works, see Meng and Harsh (1988) and references therein.

After the discovery of the Chesapeake Bay impact crater, the VCP framework was further refined by McFarland and Bruce (2006). This update revised hydrostratigraphic units and incorporated the Chesapeake Bay impact crater, describing its effect on groundwater movement and the position of the freshwater/salt-water interface. Since 2006, several sub-regional refinements for VCP framework were completed. These refinements focused on characteristics and(or) hydrologic conditions of the Piney Point aquifer (McFarland, 2017), the Potomac aquifer (McFarland, 2013), and the area southeast of the James River (Caldwell and McFarland, 2022).

Separately, a hydrogeologic framework for the Virginia Eastern Shore was developed and published by Richardson (1994). This framework was updated by McFarland and Beach (2019) to incorporate new geologic data, confirming the surficial, upper, middle, and lower Yorktown-Eastover aquifers, and defined and described unique geology within three paleochannels that transect and incise the Eastern Shore.

“Hydrogeologic Framework and Ground-Water Flow in the Fall Zone of Virginia” (McFarland, 1999) determined that out of approximately 40–45 inches of annual precipitation in the Fall Zone, less than 1 inch per year reaches the underlying VCP confined aquifer system as recharge. Where rivers intersect buried portions of confined aquifers near the Fall Zone, approximately 2 inches per year may enter the confined aquifer system as recharge. Regional recharge of the confined VCP aquifer system may have shifted away from the Fall Zone and toward major pumping centers through greater downward leakage.

1.4.2 Groundwater Quality

Building on the work of Focazio et al. (1993) and others, the most recent study of regional groundwater quality in the VCP was published by McFarland (2010), more than 15 years ago. This effort included compiling groundwater quality data for the period 1906 to 2007. It delineated the regional saltwater-transition zone, defined as a diffuse mixing zone where freshwater flushing from the west mixes with saltwater from the east. The saltwater transition is quantitatively represented by a chloride concentration of 250 milligrams per liter (mg/L). This value corresponds to EPA’s secondary drinking water standard, which is associated with a salty taste (details available at <https://www.epa.gov/sdwa/secondary-drinking-water-standards-guidance->

[nuisance-chemicals](#), accessed October 8, 2025). Some individual wells exhibited changing chloride concentrations, which were interpreted as localized movement of saltwater. The observed changes were generally offset by coincidental changes, and neither increases nor decreases in chloride concentration became more significant over the period of analysis. The study found no consistent landward migration of increasing chloride. From these observations, the study concluded that the current configuration of the saltwater-transition zone reflected pre-stress (pre-pumping) conditions.

The same study also analyzed sample data to determine spatial trends in groundwater quality and related processes, in the context of resource management. For instance, the geochemical evolution of groundwater types from “hard” to “soft” to “salty” was mapped for the deep Piney Point, Aquia, and Potomac aquifers. This evolution was attributed to processes that included flow velocity, residence times, sediment composition, geologic **heterogeneity**, configuration of the basement (embayments and arches, Figure 3), and the presence and influence of the Chesapeake Bay impact crater (Figures 2–4). The study identified various potential effects of withdrawals on the position of the saltwater-transition zone. These potential effects included short-term, local **upconing** and downconing of saltwater in response to nearby pumping, as well as longer-term lateral saltwater migration. The study briefly discussed recommendations for an effective monitoring strategy to prevent saltwater intrusion.

A subsequent study by the same author further developed a strategy for monitoring saltwater movement under the present withdrawal conditions of the VCP aquifer system (McFarland, 2015). The strategy included monitoring of both the vertical component and the lateral component of saltwater movement in response to groundwater withdrawals at specific production wells, selected on the basis of their construction and position. The vertical component (upconing) would be monitored by installing an **observation well** alongside the production well. This observation well would be designed to intersect the estimated position of the 250-mg/L chloride **iso-concentration** surface below the production well, allowing detection of any increasing trend related to induced vertical migration. The lateral component of migration would be monitored by a second observation well installed at a distance of one mile from the same production well, in the direction of the 250-mg/L chloride iso-concentration surface. This observation well’s **screened interval** would be installed at a depth matching the base of the production well’s screened interval, to isolate the lateral component of saltwater migration. This strategy has shaped DEQ’s plan to install new chloride-monitoring wells in southeastern Virginia (see Section 1.4.5).

1.4.3 Domestic Groundwater Use

Key Point #2

The growing population of private domestic groundwater users in the VCP is projected to increase the total annual withdrawal rate by 200,000 to 300,000 gallons per day, on average, each year through 2050. These lawful, unpermitted withdrawals are not reported to DEQ. Instead, they must be estimated from census and water-use data.

In the VCP, most domestic groundwater users with private wells are exempt from DEQ management because their withdrawals do not exceed the regulatory thresholds for mandatory reporting or permitting. Nonetheless, domestic groundwater use accounts for a significant fraction of overall groundwater withdrawals from the VCP aquifer system. USGS has undertaken two major efforts to quantify this unreported domestic use. Pope et al. (2008) developed techniques to estimate the locations, aquifers, and amounts of water withdrawn from the VCP aquifer system by private domestic wells for incorporation into the VCP groundwater flow model (Heywood and Pope, 2009). This study estimated that over 500,000 residents, 15% of the total population of the VCP, relied on self-supplied domestic groundwater from an estimated 200,000 private wells. Most of these withdrawals were estimated to be from the shallow unconfined surficial aquifer (22%) or the deep Potomac aquifer (25%), with the remaining 53% from the intervening confined aquifer systems. The study estimated that 28% (38.5 Mgal/day) of all groundwater withdrawn from the VCP aquifer system was for self-supplied domestic use. These estimates were based on a per-capita water-use coefficient of 75 gal/day for Virginia. The results were incorporated into the current VCP flow model, its implementation for DEQ permitting, and the regional groundwater budget analyses described in this report.

For the Eastern Shore, population estimates and road densities were evaluated in a geographic information

system (GIS) to estimate self-supplied domestic well withdrawals for Accomack and Northampton counties. These withdrawal estimates were used in the Eastern Shore groundwater flow model. The majority of withdrawals are sourced from the Upper and Middle Yorktown-Eastover aquifers. In 2000, the self-supplied domestic withdrawal was estimated at approximately 2.74 Mgal/day or 29% of the overall total Eastern Shore withdrawals (7 Mgal/day).

In 2025, the self-supplied domestic groundwater withdrawals for the VCP were revised using newly developed estimation techniques (Kearns and Pope, 2025). The new study used a larger database of well records, a more recently estimated per-capita water-use coefficient of 80 gal/day, and a new method of using census-block data to map the population of self-supplied domestic groundwater users. The results indicated that, among the VCP's domestic wells in 2020, approximately 21% of wells withdrew from the surficial aquifer (combined 9.00 Mgal/day), 35% of wells withdrew from the Yorktown-Eastover aquifer (10.26 Mgal/day), 31% of wells used the Potomac aquifer (11.45 Mgal/day), and the remaining 13% of wells were spread among the remaining confined aquifers and the basement bedrock (combined 7.28 Mgal/day). The resulting total domestic withdrawal in the VCP was estimated at 37.99 Mgal/day, similar to the 2008 estimate of 38.5 Mgal/day. The aquifer-specific domestic withdrawal values are included in figures and tables of DEQ's reported groundwater use data in Section 1.5.2, below. The revised estimates will also be incorporated into future versions of the VCP flow model.

According to the new USGS study, the 2010–2020 increase in the self-supplied VCP population translated to an average annual increase of about 200,000 gal/day in the total domestic groundwater withdrawal from VCP aquifers (Table 2). For each VCP locality identified in the study, DEQ compared the 2020 self-supplied domestic population (in Table 4 of that study) with the total population of the locality reported for 2020 (Table 2; University of Virginia Weldon Cooper Center for Public Service, 2025). Note that the Weldon Cooper Center's data included the entire area of each locality but the USGS data included only those areas located in the VCP, that is, east of the Fall Zone. Using the 2020 data, DEQ computed the fraction of each locality's total population that consisted of self-supplied domestic groundwater users in the VCP. Making the assumption that this fraction would remain constant in the future, DEQ applied the same fraction to the localities' projected total populations in 2030, 2040, and 2050, and summed the results across all of the localities. The results indicate that, in coming decades, the total domestic withdrawal from private wells in the VCP aquifer system will likely continue to increase by 200,000–300,000 gal/day each year (Table 2). This range is a rough estimate, subject to change, but it offers a reasonable forecast for planning.

Table 2: Private domestic groundwater use in the VCP

Year	Estimated self-supplied population in VCP ¹	Estimated total domestic use (Mgal/day) based on per-capita usage of 80 gal/day ²	Average annual increase by decade (Mgal/day)
2010	449,495	36	-
2020	475,332	38	0.2
2030	503,288	40	0.2
2040	529,262	42	0.2
2050	563,271	45	0.3

¹ 2010 and 2020 values from Kearns and Pope (2025). Future values computed from Virginia population projections (University of Virginia Weldon Cooper Center for Public Service, 2025) for each VCP locality, by applying the 2020 self-supplied fraction of that locality's total population from Kearns and Pope (2025).

² Refer to Kearns and Pope (2025) and references therein.

1.4.4 Groundwater Flow Models

Key Point #3

Major withdrawals, especially at paper mills near Franklin and West Point, have caused inland groundwater levels to decline below sea level, altering the predevelopment flow pattern in the VCP. Multiple lines of evidence show that groundwater now tends to flow inward from the margins toward the withdrawal centers and downward from higher to lower units in the VCP aquifer system. See also Sections 1.5.2 (esp. Table 4), 2.2, and 2.4.3 of report.

Key Point #4

These conditions cause land subsidence (sinking) and the potential for regional saltwater intrusion (saline water moving into freshwater aquifers). **Chloride concentrations in the aquifer system are increasing locally in some parts of Eastern Virginia and on the Eastern Shore.** See also Section 3.5.2.

VCP Groundwater Flow Model

“Simulation of Groundwater Flow in the Coastal Plain Aquifer System of Virginia” (Heywood and Pope, 2009) describes the original version of the groundwater flow model that DEQ currently uses to evaluate groundwater withdrawal permit applications in the Eastern Virginia GWMA. The primary purpose of the model is to estimate regional changes in water levels in the confined aquifer system resulting from groundwater withdrawals to help evaluate withdrawal permits. The model was constructed using the 2006 hydrogeologic framework of the VCP that was discussed above (McFarland and Bruce, 2006). The model includes the Eastern Shore, but its focus is the mainland VCP. A separate groundwater flow model developed exclusively for the Virginia Eastern Shore is described below.

The VCP groundwater flow model’s domain encompasses an area from Stafford, Virginia, south to the adjacent Coastal Plain of North Carolina, and from the Fall Zone to the Eastern Shore of Virginia, including portions of Maryland, and extending under the Atlantic Ocean to the continental shelf (Figure 2). The VCP area north of Stafford, Virginia, is outside the model domain boundary due to the incomplete characterization of this geologically complex area along the Fall Zone, which is also somewhat isolated from the rest of the VCP aquifer system.

The model boundaries extend vertically from land surface to bedrock. The lateral and bottom boundaries of the model domain are designated as no-flow boundaries, with two exceptions. Lateral boundary flow is set to model underflow to the north, out of the model into Maryland, and from the Piedmont physiographic province into the model over the Norfolk structural arch. These two boundary conditions were partially changed from their original no-flow condition to specified flux boundaries to aid in calibrating the model to eliminate differences in water levels over the Norfolk Arch and to better model large groundwater withdrawals from the Aquia aquifer in southern Maryland.

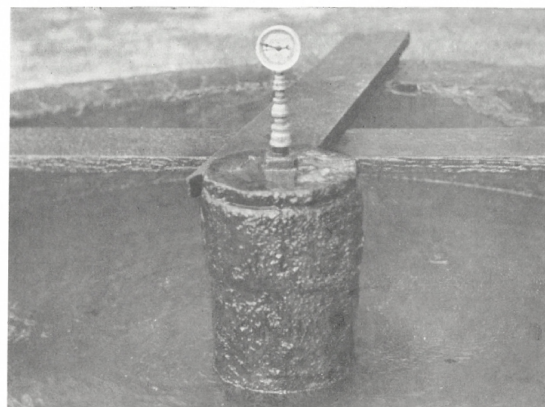
The model used a period of 1890 through 2003 to calibrate to 7,183 historic water level observations on 497 observation wells, most in the Potomac aquifer, primarily from Virginia and Maryland with some from North Carolina, starting in the early 1900s to 2003. Before the onset of extensive well installation and pumping, the VCP featured widespread artesian conditions and some areas with flowing artesian wells, as seen in Figure 7. These features reflected the underlying conditions, in which the confined aquifers of the VCP were under pressure sufficient to maintain their **potentiometric surfaces** above sea level (Figure 8), with seaward **hydraulic gradients**. However, increasing unregulated use of groundwater resources throughout the 20th century resulted in groundwater-level declines of more than 200 feet near major pumping centers (Heywood and Pope, 2009). Sustained groundwater withdrawals resulted in potentiometric surfaces declining below mean sea level and a landward hydraulic gradient that created the potential for regional saltwater intrusion (Figure 9).

Long-term declines in water levels can also result in land subsidence, which has been documented in the VCP (Eggleston and Pope, 2013). Recent years have seen growing interest and investment in monitoring this

subsidence. As a result, Virginia now has the most extensive network of **extensometers** installed in the United States east of the Mississippi River. Currently, there are four active extensometers in the VCP, each positioned near major groundwater withdrawals or planned groundwater injection sites (Figure 10). A fifth is under construction in Newport News, near another planned injection site. This network of extensometers helps assess subsidence related to groundwater withdrawal or injection in the VCP aquifer system. The planned addition of satellite-based Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) monitoring at the active extensometer sites will provide additional accuracy and greater resolution in the evaluation of the data. Additional information can be found on <https://www.usgs.gov/>.



(a) Monitoring well near Franklin, Virginia, in 1941. Water levels rose to about 7 feet above land surface when the well was first installed to a depth of 600 feet below land surface.



(b) Well cap with gauge measuring the pressure generated by artesian well near Norfolk, Virginia.



(c) Flowing artesian well near Norfolk, Virginia.

Figure 7: Historic photographs reproduced from [Cederstrom \(1945\)](#).

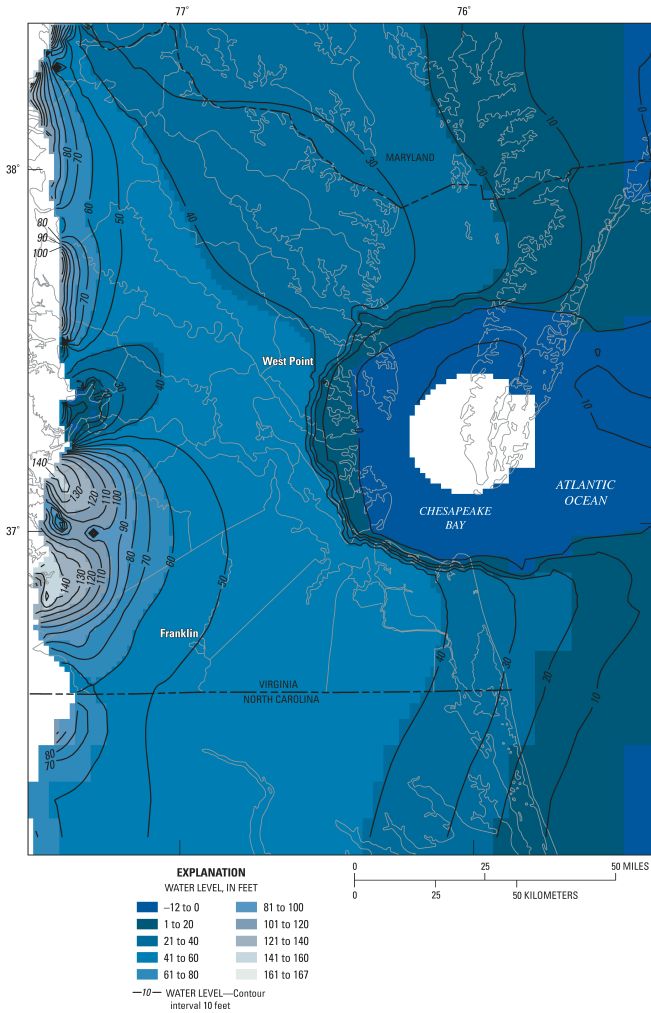


Figure 8: Modeled pre-industrial water levels in the Potomac aquifer. Values in feet above the National Geodetic Vertical Datum of 1929 (roughly sea level). Reproduced from Heywood and Pope (2009).

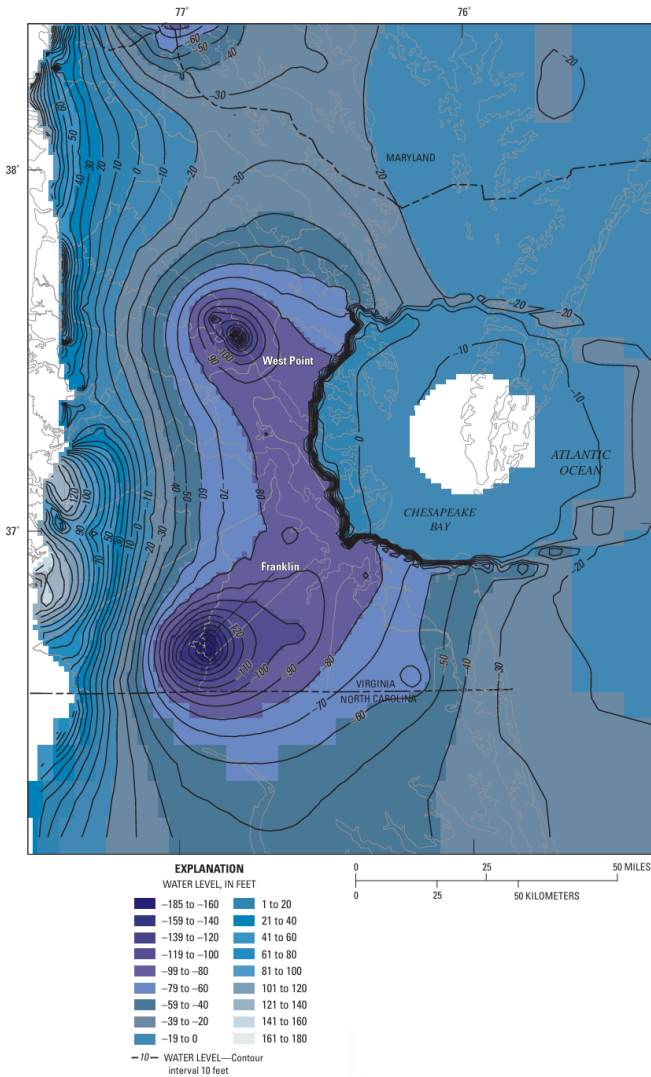


Figure 9: Modeled 2003 water levels in the Potomac aquifer. Values in feet above the National Geodetic Vertical Datum of 1929 (roughly sea level). Reproduced from Heywood and Pope (2009).

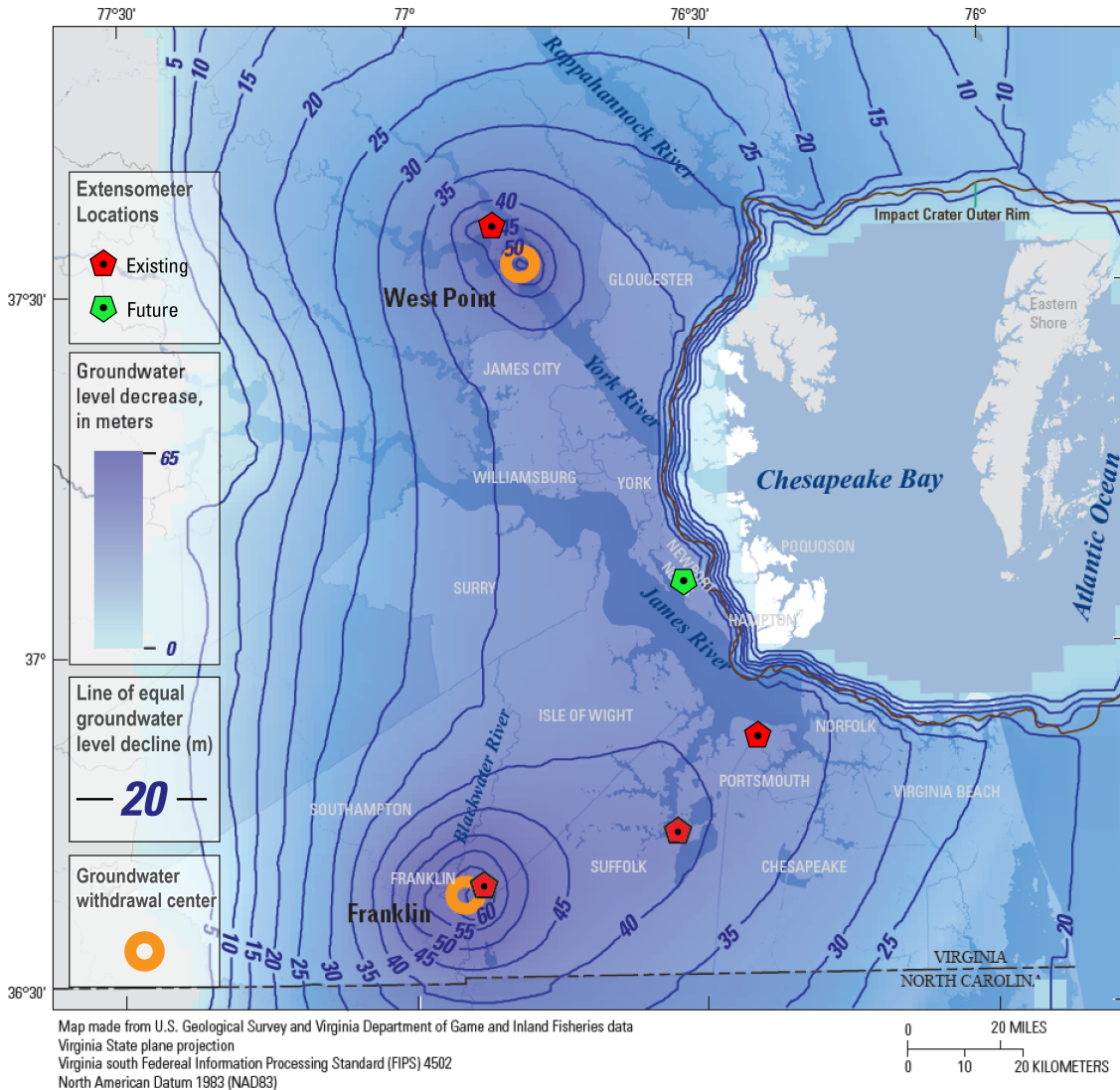


Figure 10: Map of the Virginia Extensometer Network, with four existing extensometers (red) and a fifth extensometer under construction (green). Contours and shading show modeled historical groundwater-level declines (meters) in the Potomac aquifer, from pre-industrial conditions to 2003. Figure available at <https://www.usgs.gov/media/images/virginia-extensometer-network> (accessed October 8, 2025); adapted from Eggleston and Pope (2013).

Virginia Eastern Shore Groundwater Flow Model

“Simulation of Groundwater-Level and Salinity Changes in the Eastern Shore, Virginia” (Sanford et al., 2009a) describes the numerical groundwater flow model that DEQ currently utilizes to evaluate groundwater withdrawal permit applications in the Eastern Shore GWMA. The model was developed as an improvement over the previous model (Richardson, 1994) in that it not only simulates water levels but also includes particle tracking functionality to simulate chloride concentrations as a proxy for saltwater intrusion and incorporates estimated domestic use. It reuses the hydrogeologic framework from the 1994 model but incorporates estimated locations and depths of two paleochannels that were only preliminarily described when the earlier model was developed. A new Eastern Shore groundwater model is currently being developed by USGS and DEQ based on the latest hydrogeologic framework by McFarland and Beach (2019). This recent framework includes three paleochannels with detailed locations, depths, lateral extents, aquifers, and confining units specific to the paleochannels. The new model should include the extents of the three paleochannels with

their aquifers and confining units, but the level of detailed hydrogeologic information needed to accurately model them may not be available.

The Virginia Eastern Shore model domain covers the Virginia Eastern Shore extending into the Maryland Eastern Shore, and offshore into the Chesapeake Bay and Atlantic Ocean for approximately 10 to 15 miles (Figure 2). The offshore areas are included to allow simulation between fresh and salty groundwater to model the saltwater-transition zone (Figure 6c). The model domain boundaries extend vertically from the land surface to the top of the St. Marys confining unit. The St. Marys confining unit functions as the lower limit of fresh groundwater flow on the Eastern Shore and is modeled as a no-flow boundary.

This model used a period of 1900 to 2003 to compile total groundwater withdrawals for calibration to 605 historic water-level observations on approximately 20 stations in the study area, each with at least one observation well but sometimes multiple collocated wells. Future water levels in the confined aquifers were simulated through 2050 using either the 2003 pumping rates (approximately 6.5 Mgal/day non-domestic) or total permitted withdrawal rates (approximately 9.1 Mgal/day non-domestic). The 2050 projections estimated that, under 2003 pumping conditions, water levels would be lower than current water levels by a few feet near the heaviest withdrawals; under the total permitted withdrawal rates, water levels would decline by as much as tens of feet. The current withdrawal rate scenario indicated that the system had nearly reached an equilibrium state where groundwater withdrawn through pumping was balanced by water leaking from above through overlying confining units.

1.4.5 Current Projects

Collaboration with USGS

DEQ and USGS are working cooperatively to carry out a planned expansion of the statewide groundwater observation well network, with funding recommended by the Eastern Virginia Groundwater Management Advisory Committee and provided through a special appropriation from the General Assembly. Approximately 20 of the new wells will be located west of I-95, to monitor other areas of the Commonwealth. East of I-95, up to approximately 19 new chloride-monitoring wells are planned for installation in southeastern Virginia, within the Eastern Virginia GWMA (refer to Section 2.1.1). These wells will support DEQ's strategy for monitoring the movement of saltwater in the confined VCP aquifer system.

The same special appropriation also supported the drilling and construction of the new West Point Extensometer, which DEQ continues to support through joint funding agreements with USGS. This is the latest addition to Virginia's growing network of extensometers, the largest of its kind east of the Mississippi River, as discussed in Section 1.4.4, above. These stations directly measure aquifer compaction related to groundwater withdrawals from the VCP aquifer system. USGS plans to add satellite-based GPS and Interferometric Synthetic Aperture Radar (InSAR) monitoring at these sites. These complementary technologies will offer a combination of high resolution and wide coverage in the monitoring of aquifer compaction and land subsidence.

DEQ and USGS are currently working together on a preliminary study of the VCP area north of Fredericksburg, including portions of Fairfax County, Prince William County, and Stafford County. This area has been excluded from previous framework studies because of its complex hydrogeology and relative isolation from the rest of the VCP. As a result, it lies outside the VCP flow model domain and cannot be evaluated with existing models. DEQ and USGS reviewed the available data for groundwater and existing water wells in that area, and staff collected samples from several wells for groundwater-quality analyses, including estimation of the groundwater age from its chemical constituents. USGS also estimated the depth to bedrock across the area by using a passive seismic survey method that exploits seismic noise signals to estimate the thickness of unconsolidated sediments overlying the bedrock. A USGS data release is in preparation.

DEQ has engaged USGS to develop a new Eastern Shore groundwater flow model based on the latest revised hydrogeologic framework, summarized above (McFarland and Beach, 2019). This model is expected to employ new software that enables greater partitioning of the aquifers and confining units to provide greater accuracy in modeling the system's variability and complexity. The new model will also account for the paleochannels that were featured in the most recent Eastern Shore hydrogeologic framework.

Finally, DEQ and USGS are cooperating to develop various enhancements to the data visualization tools noted in Section 2.1.3. Expected enhancements include groundwater-level trend information, as well as maps of the potentiometric surfaces associated with observed groundwater levels in the major VCP aquifers.



(a) DEQ geologist using a sieve to catch cuttings from mud-rotary drilling discharge.



(b) DEQ geologist washing, preparing, and reviewing samples of drill cuttings.



(c) Drill cuttings samples reconstructed into groups representing 10-foot intervals of depth below land surface, for detailed description and logging. Inset images show the sampling sieve (left) and fossil shark teeth (right). Formations and aquifers are determined using these samples, borehole geophysical logs, and other data.

Figure 11: Collection, processing, and characterization of mud-rotary drill cuttings for hydrogeological data acquisition.

Collaboration with Well Drillers

The majority of DEQ’s hydrogeological data collection occurs in coordination with commercial water-well drillers. DEQ Groundwater Characterization Geologists regularly participate in field events with drilling contractors for facilities that are subject to Virginia’s Groundwater Withdrawal Regulations.⁵⁰ DEQ geologists coordinate with the drillers before and during the site work to offer technical assistance and to provide quality assurance for the groundwater withdrawal permitting process. On site, DEQ geologists use special techniques to collect and prepare drill cuttings for detailed logging (Figure 11). They also work with drillers to collect geophysical log data from new production wells, observation wells, and test boreholes. Consistent application of these techniques by DEQ’s trained and experienced geologists is vital for consistent implementation of regulatory policy across permits and across the VCP aquifer system. Between new permit applications and existing permits that require additional data collection, the list of DEQ’s future commitments continues to grow. Staffing these projects is a challenge; currently, DEQ has one team leader and two staff dedicated full-time to groundwater characterization field work in the VCP.

These DEQ field events generate high-quality data for multiple purposes. First, they enable DEQ’s Groundwater Withdrawal Permitting Program to conduct technical evaluations of the proposed withdrawals (see Section 1.6.3). Second, they allow DEQ and USGS to refine the hydrogeologic framework (see Section 1.4.1). Where new findings differ from the existing framework, DEQ makes a focused effort to obtain more geological information from the same vicinity and to reconcile the observed differences. This iterative process results in continuous improvement of the overall characterization and management of VCP groundwater resources. Efficient processing and management of the incoming data is a challenge; DEQ currently has no staff dedicated full-time to this task.

1.5 DEQ Groundwater Supply Planning

Key Point #1 (repeated)

The confined Potomac aquifer is the largest and deepest in the VCP, accounting for 70% of total reported and estimated groundwater withdrawals in the Eastern Virginia Groundwater Management Area. The confined Yorktown-Eastover aquifer system accounts for 95% of total reported and estimated groundwater withdrawals in the Eastern Shore Groundwater Management Area. **Combining the two regulated areas, the major uses of groundwater are industrial (35% of total), private domestic (34%), and public water supply (26%).** See also Section 1.2.2.

1.5.1 Plans and Reports

The “State Water Resources Plan” (State Plan) compiles and analyzes information provided to DEQ by localities through their Local and Regional Water Supply Plans, annual water withdrawal reporting, and surface-water and groundwater withdrawal permitting. DEQ analyzes and models surface water and groundwater resources from the information submitted in these reports. The first State Plan was published in 2015, and the subsequent 2020 State Plan built on this report by including water demands for 2020 and projections of future water use through 2040. The 2020 State Plan also included 20 distinct regional analyses conducted at river basin scale which allowed the evaluation of results beyond the statewide trends. The 2020 State Plan is the most current version available.

In 2020, the Virginia General Assembly Session passed legislation⁵¹ requiring the State Water Control Board to adopt regulations creating regional water supply planning areas based primarily on river basins and shared resources. This created 26 regional planning areas, subsequently reduced to 25 due to reassignments, greatly consolidating what had been a much higher number of areas. The amendments to the Water Supply Planning Regulation⁵² became effective in October 2024.

The data provided through [Regional Water Supply Plans](#) are an integral part of the State Plan. As such, each of the 25 newly established regional planning areas will need to complete and submit their respective

⁵⁰ See 9 VA. ADMIN CODE § 25-610.

⁵¹ See VA. CODE ANN. § 62.1-44.38:1.

⁵² See 9 VA. ADMIN CODE § 25-780.

Regional Water Supply Plans before the next State Plan can be developed. Regional Water Supply Plans are due to DEQ in October 2029. The next State Water Resources Plan will be completed after DEQ's compliance determination for the Regional Water Supply Plans.

The Annual Water Resources Report (Annual Report), prepared by DEQ, is submitted in October of each year to the Governor and the General Assembly.⁵³ This report focuses on water quantity and supply, summarizing reported water withdrawals for the calendar year, identifying water withdrawal trends, and providing an update on the Commonwealth's water resources management activities. Where applicable, the Annual Report also serves as a status report on activities associated with the State Water Resources Plan between periodic updates.

Water withdrawals reported to DEQ are grouped into the following categories:

- **Public Water Supply** — includes water withdrawn and treated to produce water to supply municipal and non-municipal water systems that primarily provide residential use. Such systems may also supply commercial and industrial facilities located within their service area. Public water supply does not include private and domestic well withdrawals under 300,000 gallons per month, which are not required to be reported.
- **Agriculture** — includes water withdrawn for raising livestock, fish farming/hatcheries, and general farm use, but does not include water used for crop irrigation.
- **Irrigation** — includes water withdrawn to promote crop growth, including but not limited to tobacco, corn, soybeans, turf grass, and nursery products.
- **Commercial** — includes water withdrawn for use by golf courses, local and federal installations, hotels, resorts, and correctional centers, among others.
- **Mining** — includes water withdrawn for pit dewatering, excavation, processing, and removal of bulk products such as coal, rock, sand, and gravel.
- **Industrial** — includes water withdrawn for use by industrial facilities that generally produce goods such as paper mills, food processors, pharmaceutical companies, furniture manufacturing, and concrete plants, among others.
- **Power Generation** — includes water withdrawn for fossil fuel power and nuclear power. Withdrawals or diversions of water for hydroelectric power (hydropower) generation are nearly all non-consumptive and are exempt from the annual water withdrawal reporting requirements.

1.5.2 Recent Reported Withdrawals

Table 3: Reported groundwater withdrawal by use type in the combined Eastern Virginia GWMA and Eastern Shore GWMA

Use Type	2019 - 2023 Avg. (Mgal/day)	2024		
		Total (Mgal/day)	% Change from Avg.	% of Total
Agriculture	1.220	1.065	-12.678	1.580
Commercial	2.665	2.129	-20.096	3.158
Fossil Power	0.041	0.025	-38.219	0.038
Industrial	37.434	35.586	-4.935	52.785
Irrigation	1.649	1.436	-12.944	2.130
Mining	0.008	0.009	6.220	0.013
Nuclear Power	0.351	0.354	0.896	0.526
Public Water Supply	27.999	26.813	-4.236	39.771
Total	71.366	67.418	-6.145	100.000

⁵³ See VA CODE ANN § 62.1-44.40.

Table 3 shows reported total groundwater withdrawals in the combined Eastern Virginia and Eastern Shore GWMA, grouped by use type. In 2024, the top two categories of reported groundwater use were industrial (35.6 Mgal/day) and public water supply (26.8 Mgal/day), accounting for approximately 93% of reported groundwater use within both GWMA. The 35.6 Mgal/day of groundwater withdrawn for industrial use accounted for over half of all reported withdrawals in the GWMA. Total reported withdrawals in 2024 decreased across several use types, including industrial and public water supply, that resulted in an overall reduction of about 6% from the preceding five-year average. Among the reported top 14 annual groundwater withdrawals in 2024, the two largest users in the GWMA were industrial facilities (Table 4). Of these top 14 facilities, five were industrial, eight were public water supplies, and one was commercial.

Table 4: Reported groundwater use by top 14 facilities in GWMA, 2023 and 2024

Facility	Avg. Mgal/day		Use Type
	2023	2024	
International Paper - Franklin Mill	14.450	15.311	Industrial
WestRock CP LLC - West Point	15.123	13.623	Industrial
Northwest River/Western Branch Systems	3.719	4.007	Public Water Supply
Western Tidewater Water Authority	3.860	3.926	Public Water Supply
JCSA - Central System	5.178	3.362	Public Water Supply
Portsmouth City - Lake Kilby Water Treatment Fac	2.364	2.250	Public Water Supply
Solenis LLC	2.242	2.218	Industrial
Perdue Farms	1.673	1.794	Industrial
Tyson Farms Inc - Temperanceville	1.486	1.446	Industrial
Colonial Williamsburg -System	1.038	1.047	Commercial
Norfolk City - Suffolk Wells	1.506	0.934	Public Water Supply
Smithfield Town	0.823	0.882	Public Water Supply
Franklin City Water System	0.817	0.848	Public Water Supply
Farms of New Kent	0.603	0.679	Public Water Supply
Total	54.942	52.381	

Figures 12 and 13 illustrate the specific uses of groundwater withdrawn from each source aquifer, in both GWMA. The data are also summarized in Tables 5 and 6. To produce these data and diagrams, DEQ joined the well-specific reported withdrawals with the source aquifer(s) assigned to each well in the VCP flow model (1.4.4). Some aquifer assignments were based on DEQ's detailed geological field work. Others were provisional, based on the position of the well screen(s) within the modeled layers. Use of the model's aquifer assignments limited the data set to the VCP model domain, excluding the portion of the GWMA that extends north of Fredericksburg (Figure 2). This procedure also excluded the small fraction of reported withdrawals in the GWMA that are not subject to permitting under the Groundwater Withdrawal Regulations. For wells located in the Eastern Shore GWMA, withdrawals were apportioned to the subdivided upper, middle, and lower aquifers of the Yorktown-Eastover aquifer system using information from (Pope et al., 2008). These processing steps and limitations introduced uncertainty, which is reflected in the lower precision of Figures 12 and 13 and Tables 5 and 6, in comparison with Tables 3 and 4.

Note that Figures 12 and 13 have different scales because the total withdrawal in Eastern Virginia was about 10 times that of the Eastern Shore. These figures include private domestic withdrawals estimated by USGS using 2020 census data and an average per-capita water-use coefficient of 80 gal/day (see Section 1.4.3). The other use types represent average withdrawals reported to DEQ during the period 2019–2023. It is important to note that these data sets do not include unreported withdrawals, other than the estimated private domestic use. For example, certain withdrawals for crop irrigation are subject to a higher threshold for mandatory reporting, meaning that withdrawals for irrigation and agricultural use are probably under-reported in comparison with other use types.

Of the total reported and estimated withdrawal in the Eastern Virginia GWMA (96.3 Mgal/day), the Potomac aquifer accounted for 70% (67.6 Mgal/day; Table 5). For groundwater withdrawn from the Potomac aquifer, the main uses were industrial (45%, 30.1 Mgal/day), public water supply (35%, 23.4 Mgal/day), and

private domestic (17%, 11.5 Mgal/day). Of the remaining aquifers, only the Aquia was substantially used by industry (3.0 Mgal/day). For the Virginia Beach, Piney Point, Yorktown-Eastover, and surficial aquifers, the primary use was private domestic. Of the total estimated private domestic use, 35% (11.5 Mgal/day) was sourced from the Potomac aquifer, 23% (7.5 Mgal/day) from the Yorktown-Eastover aquifer, and 26% (8.8 Mgal/day) from the surficial aquifer.

The total reported and estimated withdrawal in the Eastern Shore GWMA was 9.3 Mgal/day. The Yorktown-Eastover upper aquifer (3.9 Mgal/day) and middle aquifer (4.2 Mgal/day) together accounted for 87% of the total. The major use types were industrial (3.3 Mgal/day) and private domestic (2.9 Mgal/day), which together accounted for 67% of the total withdrawal. Notably, agriculture (0.6 Mgal/day) and irrigation (1.1 Mgal/day) together accounted for 18% of the total on the Eastern Shore. By contrast, in the Eastern Virginia GWMA, agriculture and irrigation together accounted for only 0.8 Mgal/day, less than 1% of the total reported withdrawal.

Table 5: Eastern Virginia GWMA Withdrawals by Source Aquifer and Use Type, 2019–2023 Average, Mgal/day. See Figure 12.

Use Type	Surficial aquifer	Yorktown-Eastover aquifer	Piney Point aquifer	Aquia aquifer	Virginia Beach aquifer	Potomac aquifer	Total	% of Total
Agriculture	-	-	-	-	-	0.5	0.5	0.6%
Commercial	0.1	0.2	0.1	0.0 ²	-	1.4	1.8	1.9%
Private Domestic ¹	8.8	7.5	4.0	1.3	0.2	11.5	33.3	34.6%
Fossil Power	-	-	-	0.0 ²	-	0.0 ²	0.0 ²	<0.0%
Industrial	0.3	0.1	0.7	3.0	-	30.1	34.0	35.4%
Irrigation	0.0 ²	0.0 ²	0.0 ²	0.0 ²	-	0.3	0.3	0.3%
Mining	-	-	-	-	-	0.0 ²	0.0 ²	<0.0%
Nuclear Power	-	-	-	-	-	0.4	0.4	0.4%
Public Water Supply	0.2	0.3	1.5	0.4	0.1	23.4	25.9	26.9%
Total	9.4	8.1	6.3	4.7	0.2	67.6	96.3	-
% of Total	9.7%	8.4%	6.6%	4.9%	0.2%	70.2%	100.0%	-

¹ Private domestic values are estimates of unreported withdrawals based on 2020 census data, from [Kearns and Pope \(2025\)](#).

² Non-zero reported amount less than 0.1 Mgal/day.

Table 6: Eastern Shore GWMA Withdrawals by Source Aquifer and Use Type, 2019–2023 Average, Mgal/day. See Figure 13.

Use Type	Surficial aquifer	Yorktown-Eastover upper aquifer	Yorktown-Eastover middle aquifer	Yorktown-Eastover lower aquifer	Total	% of Total
Agriculture	0.0 ²	0.2	0.2	0.2	0.6	5.9%
Commercial	0.0 ²	0.2	0.2	0.0 ²	0.4	3.9%
Private Domestic ¹	0.2	1.2	1.1	0.4	2.9	31.4%
Fossil Power	0.0 ²	0.0 ²	-	-	0.0 ²	0.1%
Industrial	-	1.1	2.1	0.1	3.3	35.1%
Irrigation	0.1	0.8	0.1	0.1	1.1	11.5%
Public Water Supply	0.1	0.5	0.5	0.1	1.1	12.1%
Total	0.5	3.9	4.2	0.8	9.3	-
% of Total	5.0%	41.6%	45.1%	8.4%	100%	-

¹ Private domestic values are estimates of unreported withdrawals based on 2020 census data, from [Kearns and Pope \(2025\)](#). Apportionment of private domestic withdrawals for the Eastern Shore's subdivided Yorktown-Eastover aquifers was determined using percentages from [Pope et al. \(2008\)](#).

² Non-zero reported amount less than 0.1 Mgal/day.

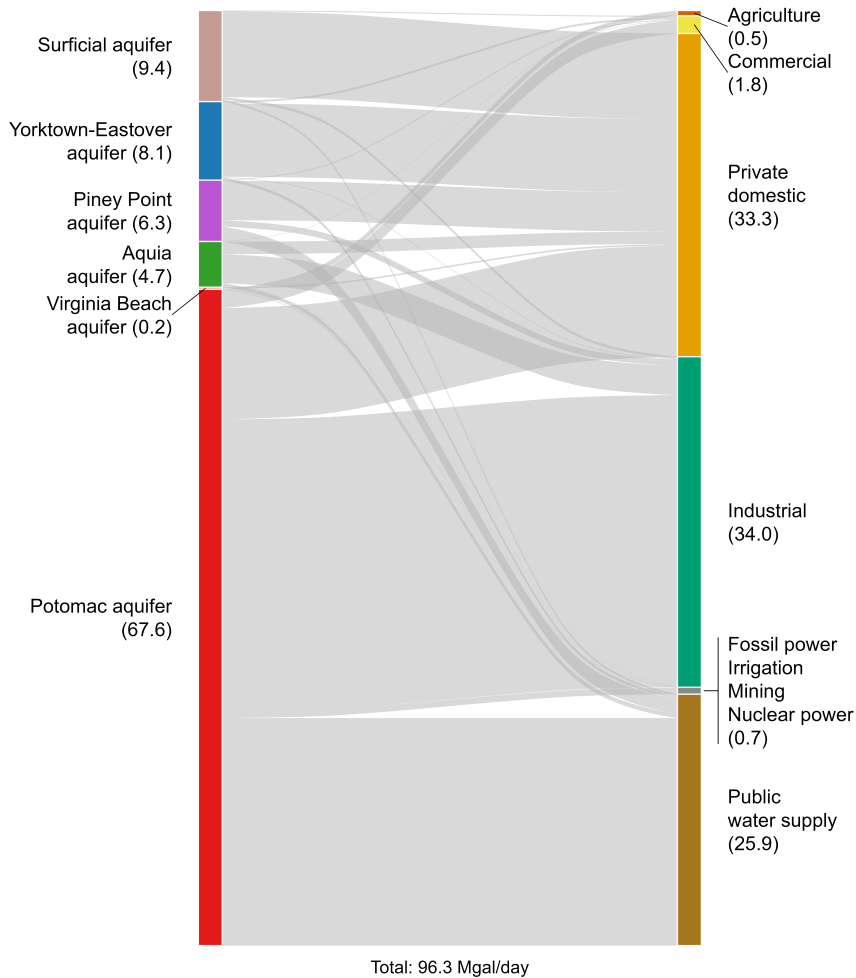


Figure 12: Reported uses of groundwater from each aquifer in the Eastern Virginia GWMA. Private domestic use estimated by USGS; other use types reported to DEQ. Average withdrawals, 2019–2023, in Mgal/day. Supporting details in Table 5.

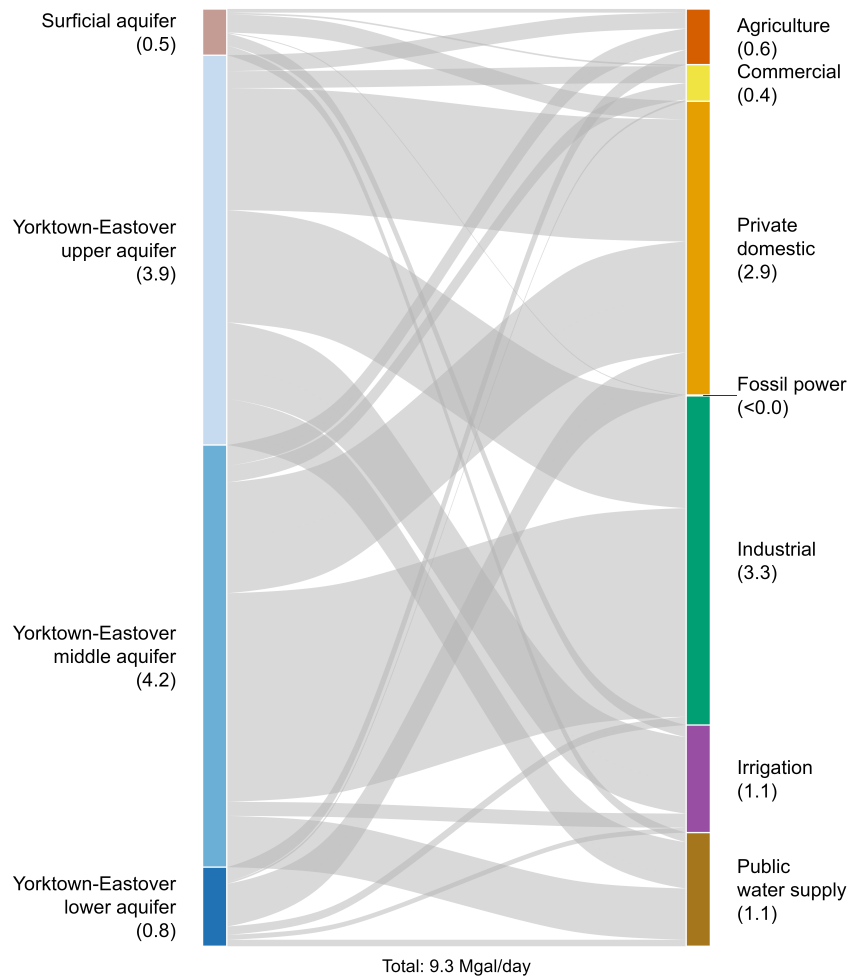


Figure 13: Reported uses of groundwater from each aquifer in the Eastern Shore GWMA. Private domestic use estimated by USGS; other use types reported to DEQ. Average withdrawals, 2019–2023, in Mgal/day. Note that the scale differs from that of the figure at left. Supporting details in Table 6.

1.6 DEQ Groundwater Withdrawal Permitting

DEQ uses the published USGS groundwater flow models, described above, to support groundwater resource-management and permitting decisions. For these purposes, DEQ contracts with Aquaveo, LLC, to perform regular model maintenance and to simulate scenarios of interest. These regularly updated versions of the VCP flow model and the Eastern Shore flow model are designated “VAHydroGW-VCPM” and “VAHydroGW-ES,” respectively.

1.6.1 Annual Simulation Method

Each year, DEQ compiles updated information on the full set of reported withdrawals from the previous year, including the well locations (coordinates), screen intervals and depths, reported withdrawal volumes, and maximum permitted annual withdrawal volumes. In addition to this regular annual maintenance, other model inputs are sometimes updated. On a frequency of one to two years, updates can include domestic pumping volumes, groundwater recharge, and measured **hydraulic heads**. On a frequency of roughly two to 10 years, other maintenance can include recalibrating hydraulic parameters, updating boundary conditions, or incorporating new control points (hydrogeologic unit-top and -bottom elevations from newly collected field data). Less frequently, a model may be rebuilt to account for updated regulatory requirements. The last recalibration of the VCP flow model was documented in the “2019 Update and Recalibration of the VAHydroGW-VCPM” (DEQ, 2019). DEQ has engaged USGS to rebuild the Eastern Shore flow model, an effort that is ongoing.

After updating the model inputs, Aquaveo runs each model to simulate future groundwater conditions based on two different scenarios. The “reported use” scenario computes the most recent five-year average withdrawal for each permitted well and assumes that pumping will continue at that constant rate for the next 50 years. The “total permitted” scenario assumes that each permitted well will pump at its maximum permitted withdrawal volume over the entire 50-year future period.

The results include maps of the simulated future potentiometric contours in each aquifer, under each withdrawal scenario. Other maps show the model grid cells where the future potentiometric surface is predicted to fall below a point representing 80% of the vertical distance from the land surface to the top of the aquifer (“critical cells”); see also Section 1.6.3. Still other maps show where the potentiometric surface is predicted to fall below the top of the aquifer, risking permanent aquifer compaction and **storage** loss. The Eastern Shore report also includes maps that show the simulated future chloride concentrations in each aquifer, under each withdrawal scenario. This feature is currently available only in the VAHydroGW-ES model.

1.6.2 Annual Simulation Results

Each year, the annual simulation results are reported to DEQ and presented to stakeholders, including the Eastern Virginia Groundwater Management Advisory Committee. Recent annual reports and presentations are available on DEQ’s website: <https://www.deq.virginia.gov> (DEQ, 2024a). For the mainland VCP, the 2023–2024 annual simulations showed that overall reported withdrawals in 2023 were similar to the annual amounts reported since about 2015 (Figures 14 and 15). The 2019–2023 average total reported withdrawal was 82.8 million gallons per day (Mgal/day), including 64.9 Mgal/day of withdrawals that occurred in Virginia (the remainder occurring in modeled areas of Maryland or North Carolina). For the same period, the average total reported withdrawal from the Potomac aquifer was 56.66 Mgal/day, or 87.8% of the total for all VCP aquifers; the next-greatest total reported withdrawal occurred in the Aquia aquifer, at 3.44 Mgal/day, or 5.3% of the total for all VCP aquifers. This result indicates the predominance of Potomac aquifer withdrawals in the overall system.

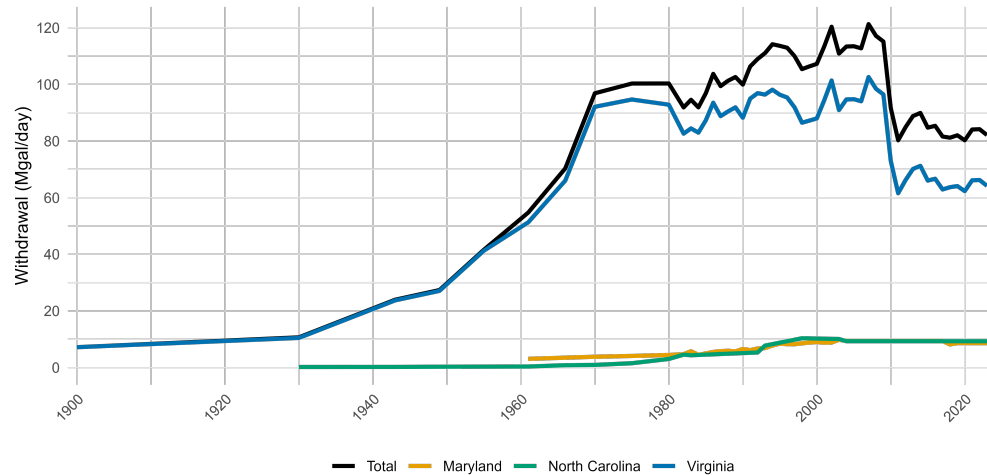


Figure 14: Simulated yearly groundwater withdrawals, in average Mgal/day, for the area of each state that is located within the Virginia Coastal Plain model domain. Data from Aquaveo, LLC (written commun.).

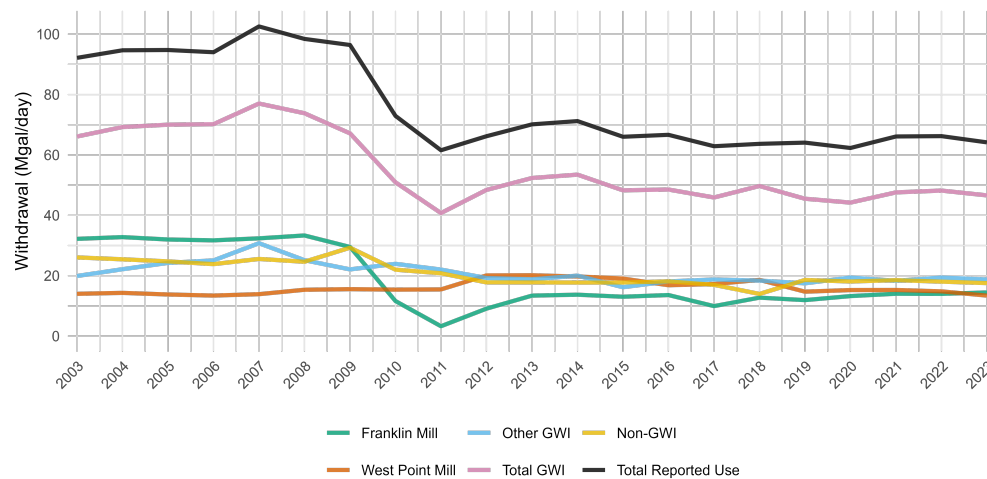


Figure 15: Yearly groundwater withdrawals, in average Mgal/day, reported to DEQ during the period 2003–2023 by selected individual facilities that were part of the VCP Groundwater Initiative (GWI) and by other facilities grouped for visualization. Data from Aquaveo, LLC (written commun.).

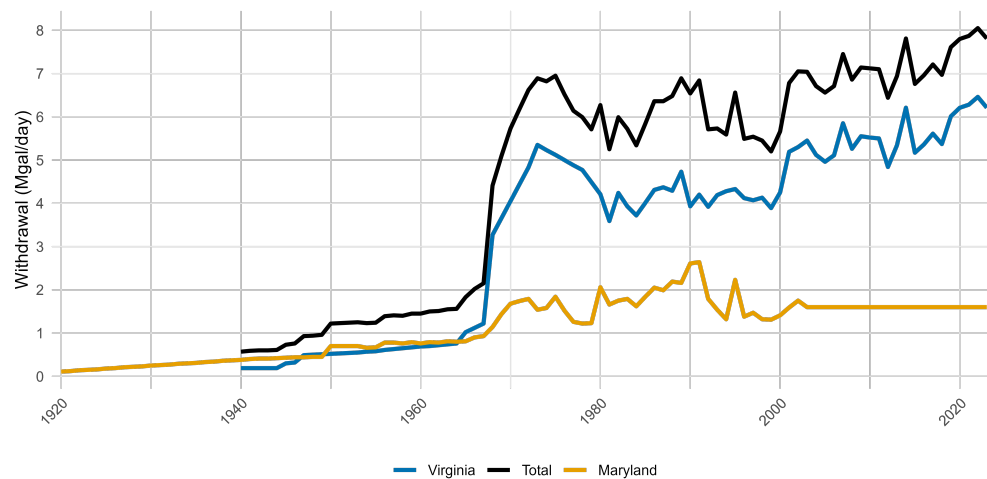


Figure 16: Simulated yearly groundwater withdrawals, in average Mgal/day, for the area of each state that is located within the Virginia Eastern Shore model domain. Data from Aquaveo, LLC (written commun.).

The 2023 “reported use” simulation predicted critical cells in the Potomac, Virginia Beach, Aquia, Piney Point, and Yorktown-Eastover aquifers. (As noted above, critical cells are model grid cells where the future potentiometric surface is predicted to fall below a point representing 80% of the vertical distance from the land surface to the top of the aquifer.) Figure 17a illustrates the mapped extent of all predicted critical cells, in any aquifer, for the annual simulations completed in 2015. These included the “reported use” scenario (50-year projection based on reported withdrawals from 2014) and the “total permitted” scenario (50-year projection based on annual maximum withdrawal limits starting in 2015). For comparison, Figure 17b shows the results of the corresponding 2017 simulations, and Figure 17c shows the results of the corresponding 2024 simulations. Between Figure 17a and Figure 17b, a notable decrease occurred in the extent of “total permitted” critical cells.

This improvement reflected an important historical milestone that is noted in DEQ’s annual report of 2023–2024. Between 2014 and 2017, DEQ undertook the “VCP Groundwater Initiative” (GWI) to reduce the historical over-allocation of the groundwater resource by negotiating lower maximum annual withdrawal limits for each of the top 14 permitted groundwater users. Before implementation of the initiative, these 14 facilities were permitted a combined maximum withdrawal equivalent to 146.54 million gallons per day. Currently, the same 14 facilities are permitted a combined maximum withdrawal equivalent to 73.59 million gallons per day, a reduction of 50% from the original combined maximum. The largest users adopted a schedule of tiered reductions during the current permit term (2017 to 2027). These reduced limits were first incorporated into the 2017 “total permitted” simulation, yielding the decrease observed between Figures 17a and 17b. The tiered reductions in annual withdrawal limits did not immediately affect actual groundwater use, so there was no corresponding decrease in the extent of “reported use” critical cells. Overall reported withdrawals have remained relatively level since 2015 (Figure 15). By 2023, a modest decrease was observed in the extent of “reported use” critical cells, especially in the northwestern area of the VCP (Figure 17c). Further improvement may occur as VCP GWI permittees implement the final, lowest tiers of their annual withdrawal limits under the current permit term. Related issues are considered in Section 2.2, below.

For the Eastern Shore, the 2023–2024 annual simulations showed that overall reported use was 6.21 Mgal/day. This value was near the previous year’s historic high of 6.46 Mgal/day, continuing on a trend of increasing withdrawals (Figure 16). Among the aquifers on the Eastern Shore, the most heavily used were the Middle Yorktown-Eastover aquifer (3.24 Mgal/day, or 50.6% of the total) and the Upper Yorktown-Eastover aquifer (2.32 Mgal/day, or 37.3% of the total). The surficial aquifer and the Lower Yorktown-Eastover aquifer each accounted for about 0.3 Mgal/day, or 5% of the total. The “total permitted” simulation predicted only one critical cell in the Middle Yorktown-Eastover aquifer, located in central Accomack County. However, the VAHydroGW-ES model predicted that certain coastal areas would see chloride concentrations above the federal secondary drinking water standard of 250 mg/L. These increases were predicted in the Middle and Lower Yorktown-Eastover aquifers near Chincoteague in Accomack County and near Cape Charles and on the Occohannock Neck in western Northampton County (Figure 18).

Note that the same 2023–2024 iteration of each model used in this section, VAHydroGW-VCPM and VAHydroGW-ES, was also used by USGS to compute detailed regional groundwater budgets. That analysis appears in Section 2.4, below.

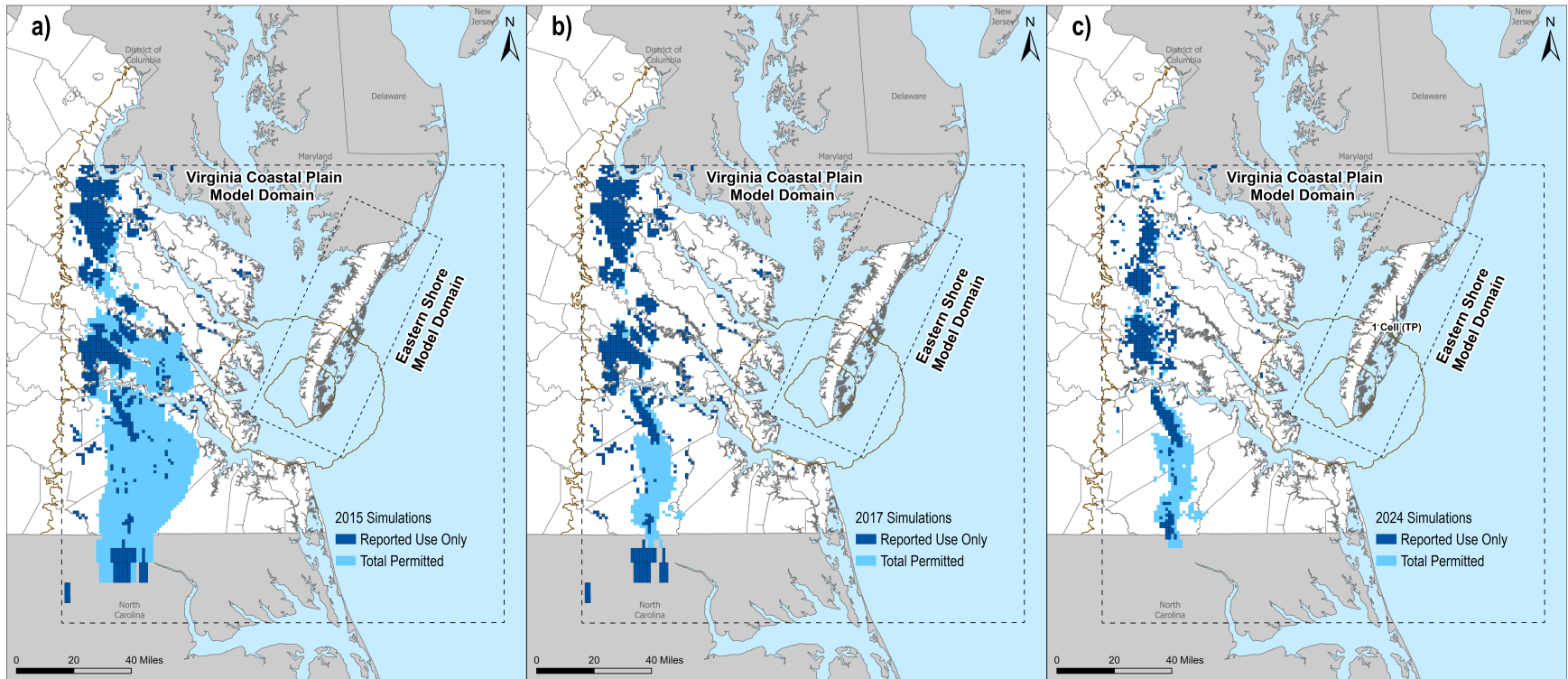


Figure 17: The mapped extent of critical cells predicted in 50-year projections of the “reported use” scenario (dark blue areas) and the “total permitted” scenario (light blue and dark blue areas combined). Simulations completed in (a) 2015 (with reported use data through 2014); (b) 2017 (with reported use data through 2016); and (c) 2024 (with reported use data through 2023). Adapted from [DEQ \(2024a\)](#) with additional data from Aquaveo, LLC (written commun.).

VAHydroGW-ES 2023 Reported Use Simulation Middle Yorktown-Eastover Chloride Concentrations

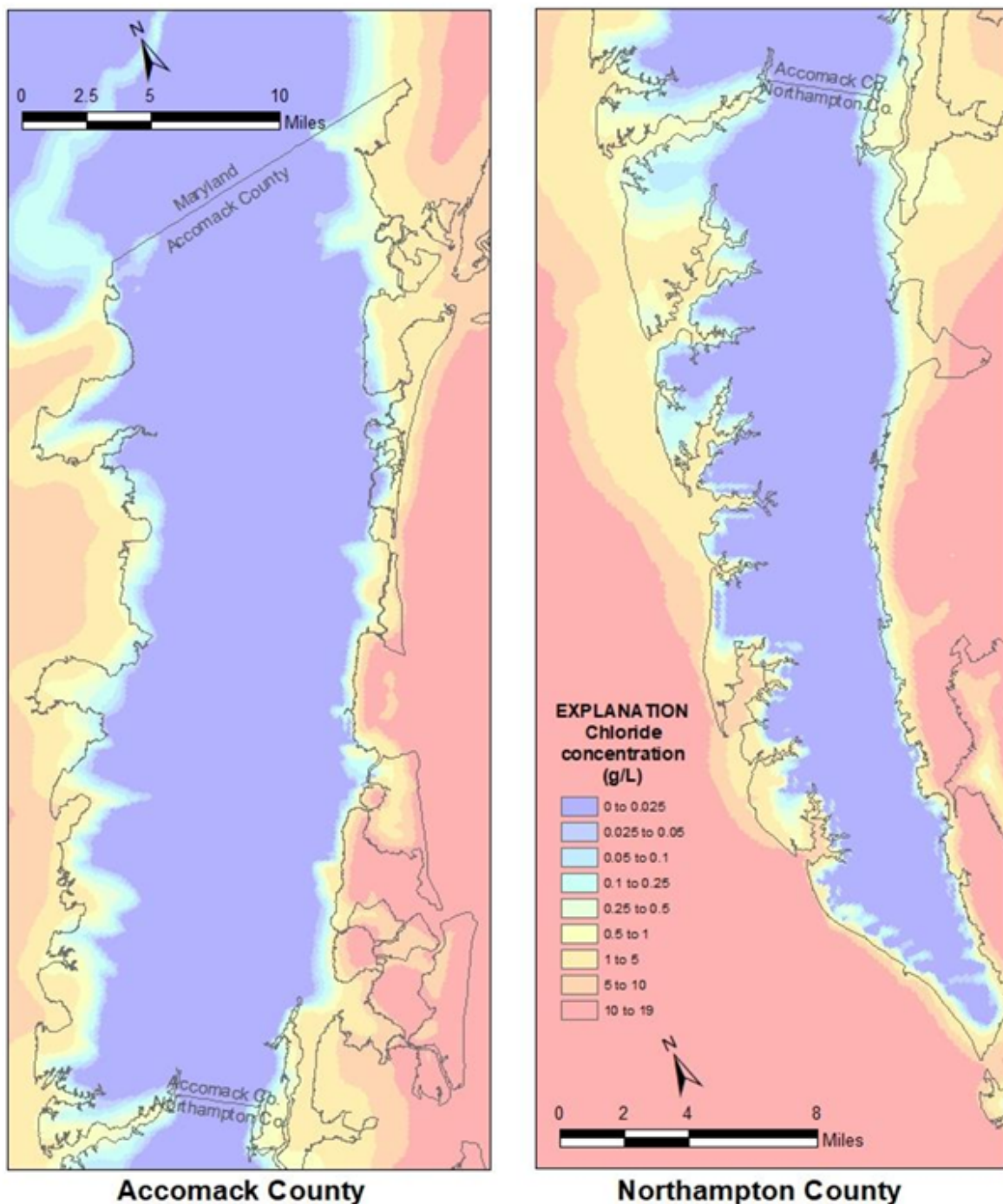


Figure 18: Chloride concentrations predicted for the Middle Yorktown-Eastover aquifer in 50-year projections of the “reported use” scenario for the Virginia Eastern Shore, based on 2023 data. Reproduced from [DEQ \(2024b\)](#).

1.6.3 Technical Evaluations

The updated VAHydroGW-VCPM and VAHydroGW-ES flow models are used in technical evaluations of individual groundwater withdrawals that are proposed in permit applications to DEQ. Under the Commonwealth of Virginia’s Groundwater Withdrawal Regulations,⁵⁴ a technical evaluation is required for DEQ to issue a permit for a new withdrawal, an expanded existing withdrawal, or a reapplication of a current withdrawal. For the purpose of evaluating a proposed withdrawal, DEQ compiles a package of supporting information and documentation. Key details include well data (location and screen interval/depth, documented on a well completion report), hydrogeologic data (unit-top and -bottom elevations, geophysical logs), aquifer-test results for the facility, and the apportionment of the permitted withdrawal amount to specific wells at the facility.

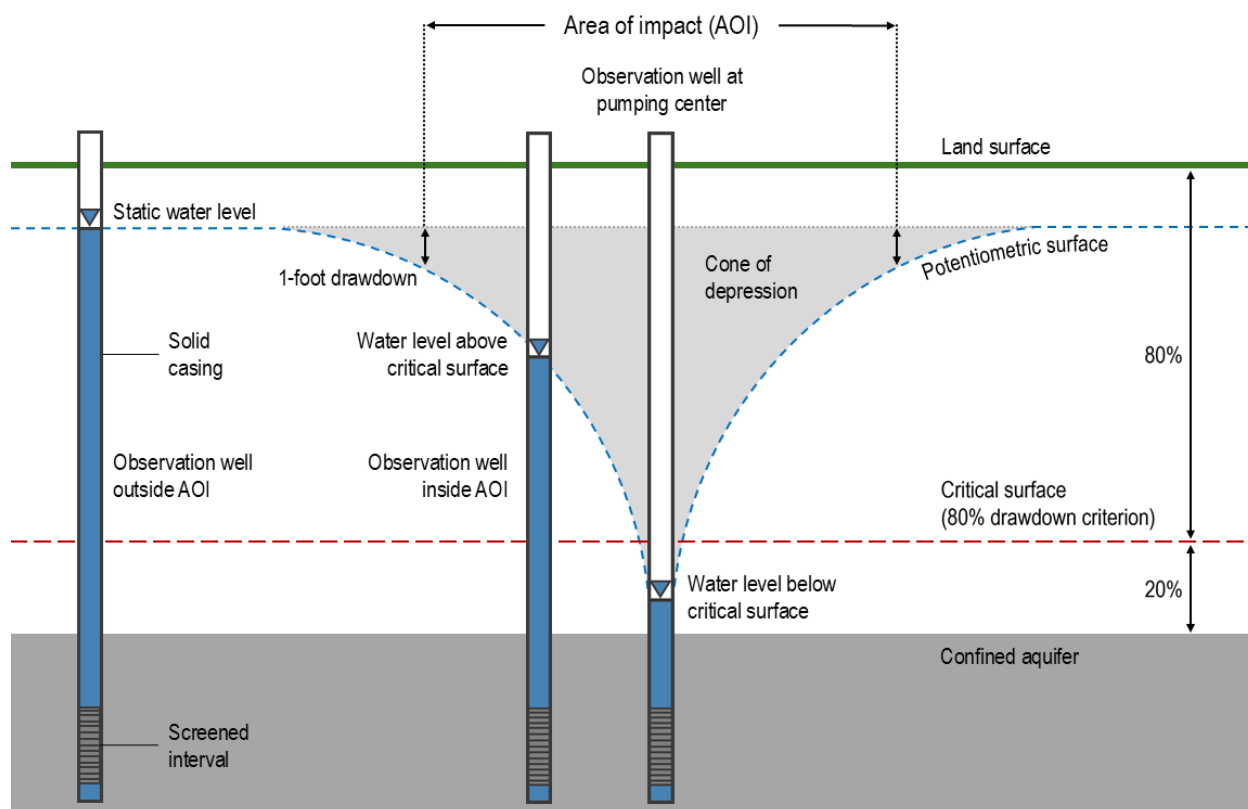


Figure 19: Diagram of key concepts in groundwater monitoring and withdrawal permitting. In the shaded area, the potentiometric surface forms the **cone of depression**. Its slope (the hydraulic gradient) increases towards the pumping center. By regulation, the area of impact is defined as the area where at least one foot of water-level decline is predicted by simulation. Multiple observed water levels are noted in relation to the critical surface, defined as 80% of the vertical distance from land surface to the aquifer top. Simulated levels above the critical surface satisfy the 80% drawdown criterion for permitting.

Using this information, Aquaveo runs the updated flow model’s “total permitted” simulation, both with and without the additional proposed withdrawal, to simulate the stabilized effects from the proposed withdrawal in combination with the stabilized combined effects of all existing lawful withdrawals. In practice, “stabilized effects” refers to groundwater-level conditions that are predicted to occur 50 years in the future. This process determines the area of impact (AOI), the areal extent in each aquifer where the model predicts one foot or more of drawdown (Figure 19). It also evaluates the 80% drawdown criterion (Figure 19) by determining whether the AOI intersects any existing critical cell in the baseline “total permitted” simulation

⁵⁴See 9 VA. ADMIN CODE § 25-610.

and whether the proposed withdrawal would create any new critical cell. If the proposed withdrawal does not satisfy the 80% drawdown criterion, then the permit is typically denied. The evaluation criteria include certain exceptions that prioritize permit applications for human consumption.⁵⁵

The technical evaluation also considers the proposed withdrawal's potential effects on groundwater quality, including saltwater intrusion into aquifers. For the Eastern Shore, it identifies any predicted chloride increases or saltwater "upconing" (vertical migration induced by local pumping). The results also present information to compare simulated water levels with observed water levels at the locations of nearby observation wells in the DEQ-USGS network.

Sometimes, DEQ also requests a determination of the estimated maximum volume that would meet the evaluation criteria. In these cases, Aquaveo performs iterative simulations of different withdrawal volumes until the maximum-passing amount is identified. This procedure is discussed further in Section 2.5.3, where it was used to estimate the varying groundwater availability in different regions of the VCP.

⁵⁵See 9 VA. ADMIN CODE § 25-610-110.

2 Groundwater Levels

2.1 Groundwater-Level Monitoring

2.1.1 Statewide Groundwater Observation Well Network

Virginia’s statewide groundwater **observation well** network provides high-quality data to identify and infer spatial locations of **hydrogeologic** units and to monitor both groundwater levels and groundwater quality in the VCP **aquifer** system. The statewide network is cooperatively maintained by DEQ and the USGS Virginia and West Virginia Water Science Center. Table 7 displays the number of wells currently operated and maintained by each agency. DEQ funds and operates most of the wells included in the network. As described in Table 7 and displayed in Figure 20, observation wells are located throughout the Commonwealth, but there is a higher density of well locations in the high groundwater withdrawal localities associated with the Eastern Shore and Eastern Virginia Groundwater Management Areas (GWMAs). Within the Eastern Virginia GWMA, coverage is less dense in the central and northern areas that were incorporated more recently, when the GWMA expanded in 2014.

Table 7: Statewide Groundwater Observation Well Network

Operator (Well Count)	Funding Cooperator (Well Count)	Collection Frequency	Eastern Shore GWMA	Eastern Virginia GWMA	Outside GWMAs	Total
DEQ (306)	DEQ (371)	Continuous	11	99	20	130
		Periodic	59	99	18	176
USGS (138)		Continuous	0	12	7	19
		Periodic	0	39	7	46
	Other (73)	Continuous	3	39	7	49
		Periodic	0	24	0	24
All (444)		Area Subtotal	73	312	59	444
DEQ	Various	Projected (Future)	14	25	3	42

Groundwater observation wells can occur singly but often are grouped as multi-well research stations that monitor multiple **hydrogeologic** units or sometimes multiple zones within a single unit. Figure 20 shows the distribution of wells and indicates the frequency of groundwater-level data collection across Virginia’s Coastal Plain and Eastern Shore. Groundwater-level data are collected from monitoring wells at regular monitoring frequencies that can be categorized as either periodic or continuous. Periodic groundwater level measurements typically occur quarterly (four measurements each year) and are collected manually using graduated steel tapes and/or water level meters. Continuous data collection occurs at monitoring wells that have been equipped with a pressure transducer programmed to record water-level elevations at consistent 15-minute intervals. Groundwater observation sites with continuous monitoring instruments also contain telemetry equipment that transmits recorded groundwater level data to a National Oceanic and Atmospheric Administration (NOAA) satellite system that populates the USGS National Water Information System (NWIS) database. Data transmissions occur every hour and allow public viewing of the most current groundwater level data collected from the continuous or “real-time” network of groundwater observation wells. Quarterly site visits are also performed at continuous monitoring sites to collect discrete measurements to verify that continuous monitoring instruments and telemetry equipment are recording and functioning properly.

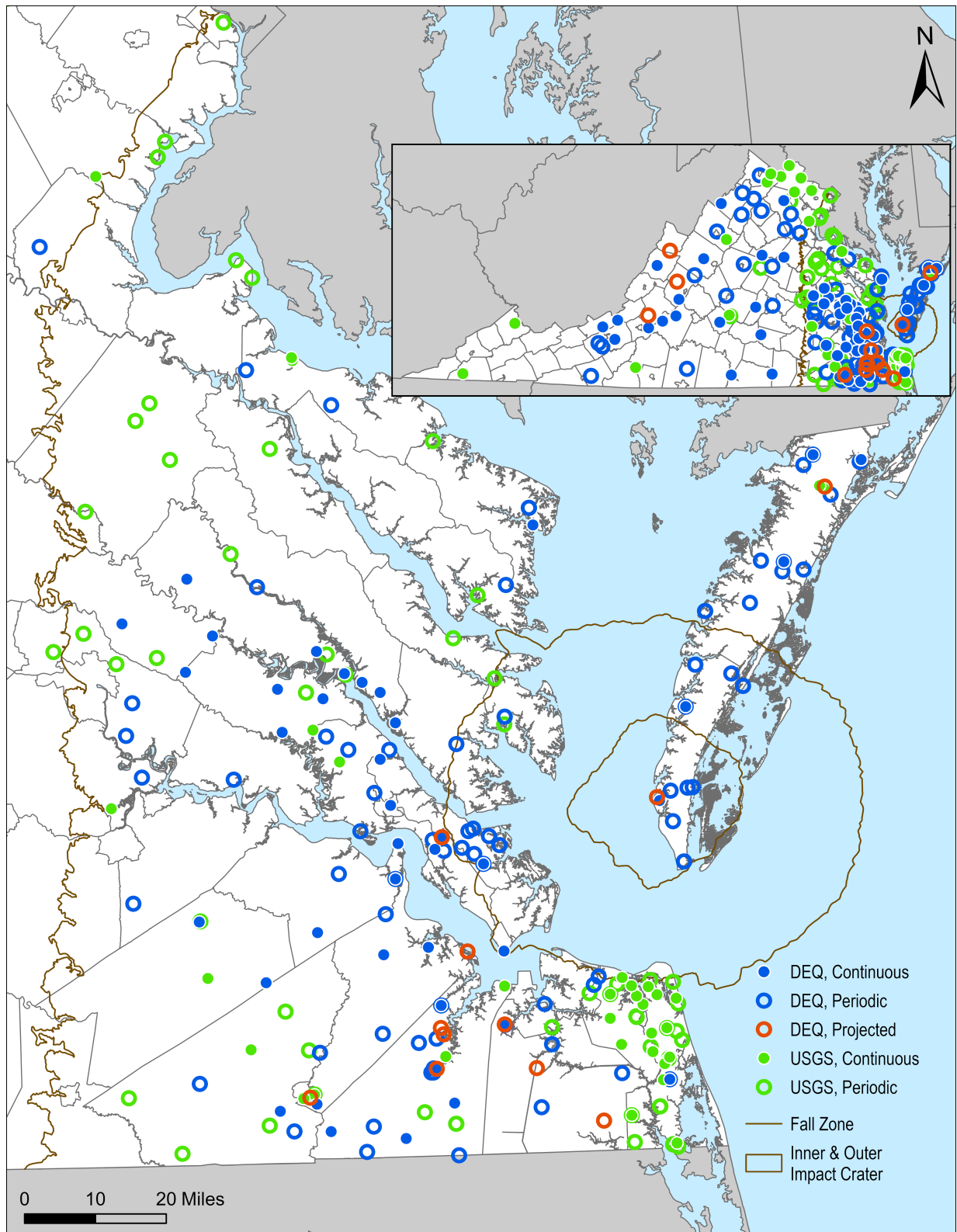


Figure 20: Virginia Coastal Plain portion of the statewide groundwater observation well network, with inset showing statewide network, indicating operating agency and frequency of water-level monitoring, plus projected locations for new wells. Fall Zone boundary from [Pope et al. \(2016\)](#), Chesapeake impact crater boundaries from [Powars and Bruce \(1999\)](#).

2.1.2 Groundwater-Level Data

DEQ and the USGS Virginia and West Virginia Water Science Center have a unique state-federal working relationship as it relates to groundwater-level data collection and evaluation. The DEQ Groundwater Monitoring Team is fully integrated into the Water Science Center's standardized workflow established for hydrologic data collection and evaluation (Kozar and Nelms, 2018). Groundwater-level data collection is conducted by DEQ and USGS staff as described in USGS "Groundwater Technical Procedures" (Cunningham and Schalk, 2011). Data collection methods include an emphasis on quality assurance/quality control and must meet strict tolerances (hundredths of feet) to ensure high quality field data is collected for subsequent uploading into NWIS for processing, analysis, and approval. Groundwater-level field measurements are input into a unique software package that is specifically designed to be used in the field and allows for efficient uploading to the NWIS database which archives and displays hydrographs that span the period of record for all observation wells within the statewide network. The internal NWIS database allows DEQ and USGS staff to evaluate hydrographs during specific periods of analysis bound by quarterly onsite data collection. The hydrographic data evaluation includes analyzing for certain parameters such as water level extremes, seasonal/long-term trends, and aquifer comparisons. As discrete groundwater-level measurements and continuous time-series data are analyzed and approved internally within NWIS, the publicly accessible NWIS website allows any user to view the analyzed and approved hydrographs from selected groundwater observation well locations. In addition, routine audits are performed by the USGS Water Science Center to validate the results of the approval process.

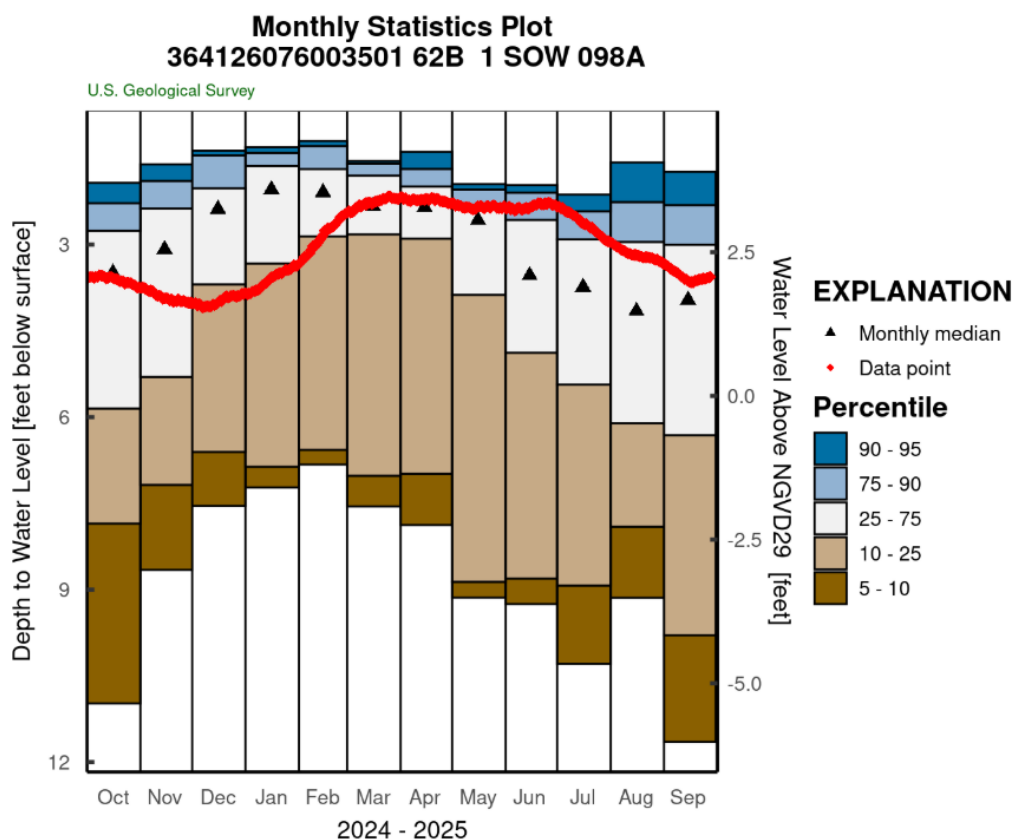


Figure 21: Hydrograph for SOW 098A in Virginia Beach, monitoring the unconfined surficial aquifer as part of the climate response subnetwork, with statistical ranges to inform drought-monitoring decisions. Exported from “VA and WV Groundwater Levels and Trends” webpage.

2.1.3 Groundwater-Level Visualization

USGS offers multiple data-visualization tools to support the display and exploration of groundwater levels in the VCP. Two interactive web tools were developed by the Virginia and West Virginia Water Science Center with support from DEQ. The web tools include features such as plotting observation well locations across Virginia and West Virginia, displaying symbology to indicate data-collection frequency and current water-level comparisons to long-term water level records, identifying monitoring well construction details and showing total number of aquifers monitored at multi-well sites.

Groundwater Levels and Trends

One of the unique custom web tools developed to identify observation well location and assess how current groundwater-level measurements compare to long-term monthly statistics is the “[VA and WV Groundwater Levels and Trends](#)” webpage. Groundwater observation well locations are plotted on a base map with symbology that identifies the data collection type (continuous or discrete) at each monitoring well location. The data collection symbols are also colored to represent the monthly percentile rank of the current water levels relative to long-term monthly statistics. The calculated percentile indicates if current water level conditions are considered low, much below or below normal, normal, much above or above normal, or high when compared to the period of record at the well. Figure 21 shows an example of the “Monthly Statistics Plot” where monthly median values (black triangles) are shown within monthly percentile bins and compared to data points collected during the past 12 months (red diamonds). Plotting water-table well data in this format supports the objectives of the Virginia Drought Monitoring Task Force (see below). In addition, detailed site pages can be selected at each groundwater observation site to provide the latest site information available from the NWIS database such as station name, well depth, and local aquifer.

Monitoring Virginia Eastern Shore Groundwater Conditions

Another useful web tool that focuses on the groundwater-level monitoring network on the Eastern Shore is the “[Monitoring Virginia Eastern Shore Groundwater Conditions](#)” webpage. This webpage displays the location of all the groundwater observation wells on the Eastern Shore. Many stations on the Eastern Shore have multiple wells installed at varying depths to monitor different hydrogeologic units such as buried **paleochannels**, the Yorktown-Eastover aquifer system, or a deeper Coastal Plain aquifer. The webpage includes a simplified **cross-section** of the Eastern Shore hydrogeologic units with background information detailing **lithologic** descriptions of each hydrogeologic unit. The color scheme and circular symbol sizing assigned to each respective hydrogeologic unit corresponds to the groundwater observation well locations shown as circles plotted on the basemap. A unique feature of this webpage allows the user to control which monitoring well locations are displayed on the map based on aquifer name to easily identify and select aquifer-specific data and locations across the Eastern Shore. Monitoring well details are available by clicking on any well location and scrolling through the tables of site information that also includes a weblink directly to the NWIS web interface for any selected well.

Time-Series Data and Applications

Within the statewide groundwater observation well network, there is a small subset of shallow observation wells that monitor how **unconfined aquifer** systems respond to climate variability. These water-table observation wells meet all the necessary criteria to be included in the [USGS Climate Response Network](#) (CRN) ([Caldwell and Fine, 2025](#)). Nationally, the CRN is designed to monitor each of the Nation’s climate divisions. At the state level, the [Virginia Drought Monitoring Task Force](#) (DMTF) has selected individual CRN wells in each of Virginia’s 13 Drought Evaluation Regions to provide the necessary groundwater-level data to serve as one of the four indicators (precipitation, streamflow, groundwater, and **reservoirs**) used by the DMTF to evaluate drought severity in Virginia ([DEQ, 2003](#)). Figure 21 shows a Monthly Statistics Plot for State Observation Well (SOW) 098A, a designated drought-monitoring well in Virginia Beach. The Monthly Statistics Plot compares daily groundwater-level data to long-term records (at least 10 years) for the current month. Based on the percentile ranking of the current month’s daily records, the DMTF will

assign the corresponding drought stage as identified by groundwater levels and consider the other stages identified by the other three drought indicators prior to issuing a declaration of a particular drought stage.

Many of the groundwater observation wells in the statewide network are installed in the **confined aquifers** of the VCP to monitor water-level response to groundwater withdrawals. Figure 22 shows a hydrograph of water levels in an observation well, representing the **potentiometric surface** of the groundwater in the confined Potomac aquifer. The hydrograph allows DEQ to monitor pumping-induced drawdown and recovery and to evaluate how changing stresses influence the response of the aquifer system. When multiple time-series observation sites are incorporated into groundwater flow models, the future projections can provide valuable results to take into consideration during groundwater resource management decisions, such as groundwater withdrawal permitting.

Continuous data

55B 91 Sow 252 a - USGS-363949076542602

[Subscribe to WaterAlert](#)



Figure 22: Hydrograph for SOW 252A in Isle of Wight County, showing water levels in the confined Potomac aquifer and variation caused by pumping effects (USGS, 2024).

2.2 Historical Analysis of Withdrawals and Effects

Key Point #3 (repeated)

Major withdrawals, especially at paper mills near Franklin and West Point, have caused inland groundwater levels to decline below sea level, altering the predevelopment flow pattern in the VCP. Multiple lines of evidence show that groundwater now tends to flow inward from the margins toward the withdrawal centers and downward from higher to lower units in the VCP aquifer system. See also Sections 1.4.4, 1.5.2 (esp. Table 4), and 2.4.3 of report.

To illustrate the utility of groundwater-level data for evaluating the condition and behavior of the VCP aquifer system, this section presents a historical analysis of VCP withdrawals and their observed effects. As noted in Section 1.4.4, present-day groundwater conditions are dominated by the effects of large inland withdrawals that have altered the predevelopment pattern of groundwater flow. These longstanding withdrawals have caused two persistent regional “**cones of depression**” to develop in the Potomac aquifer’s potentiometric surface, where the surrounding groundwater levels decline towards the pumping center. The

cones of depression are centered on two historic Virginia paper mills, one located near the City of Franklin and the other near the Town of West Point (Figure 10). This historical analysis focuses on the Franklin Mill because its total groundwater withdrawal has fluctuated widely over time, inducing a major response in the observed groundwater levels across the region.

2.2.1 Historical Withdrawals

The Franklin Mill began commercial operation as a pulp and paper mill in 1938 (Bearss, 2001). The mill facility is located in southwestern Isle of Wight County, just across the Blackwater River from the City of Franklin. The mill's wellfield forms a roughly six-mile line, extending north and south of the facility (Figure 23a). The wells supply groundwater, primarily from the confined Potomac aquifer, for the mill's industrial processes. The facility holds a groundwater withdrawal permit from DEQ (Permit No. GW0042001/GWI000192, effective July 1, 2017, expiring June 30, 2027).

In 2024, the Franklin Mill reported a total withdrawal of 15.3 Mgal/day, making it the largest user of groundwater in the regulated area of the VCP (Table 4) and accounting for 43% of total industrial withdrawals in the regulated area (35.6 Mgal/day; Table 3). The only other facility to report a comparable withdrawal (13.6 Mgal/day) was the West Point Mill (Permit No. GW0005101/GWI000085, effective July 1, 2017, expiring June 30, 2027). The West Point Mill is another historic pulp and paper mill, located in King William County near the Town of West Point (Figure 23). It also withdraws primarily from the Potomac aquifer but has historically used the Piney Point aquifer as a secondary source. Within the regulated areas of the VCP in 2024, these two paper mills together (28.9 Mgal/day) accounted for 43% of the total reported groundwater withdrawal across all aquifers and use types (67.2 Mgal/day).

The 2024 reported withdrawals were generally consistent with historical levels. These facilities have been the largest users of VCP groundwater for decades, taking turns in the top position. Together, they have consistently accounted for almost half of the overall total reported withdrawals from the VCP (Figure 15). For additional context, the upper portion of Figure 24 shows the history of various withdrawals from the Potomac aquifer, including the two paper mills' withdrawals, the combined other permitted withdrawals, and the estimated domestic withdrawals, as well as the overall sum of these components. The lower panels of Figure 24 show the paper mills' monthly reported withdrawals alongside hydrographs from nearby observation wells. There is no consistent record of reported withdrawal data before 1982, but withdrawals can be inferred from their effects on the water-level record.

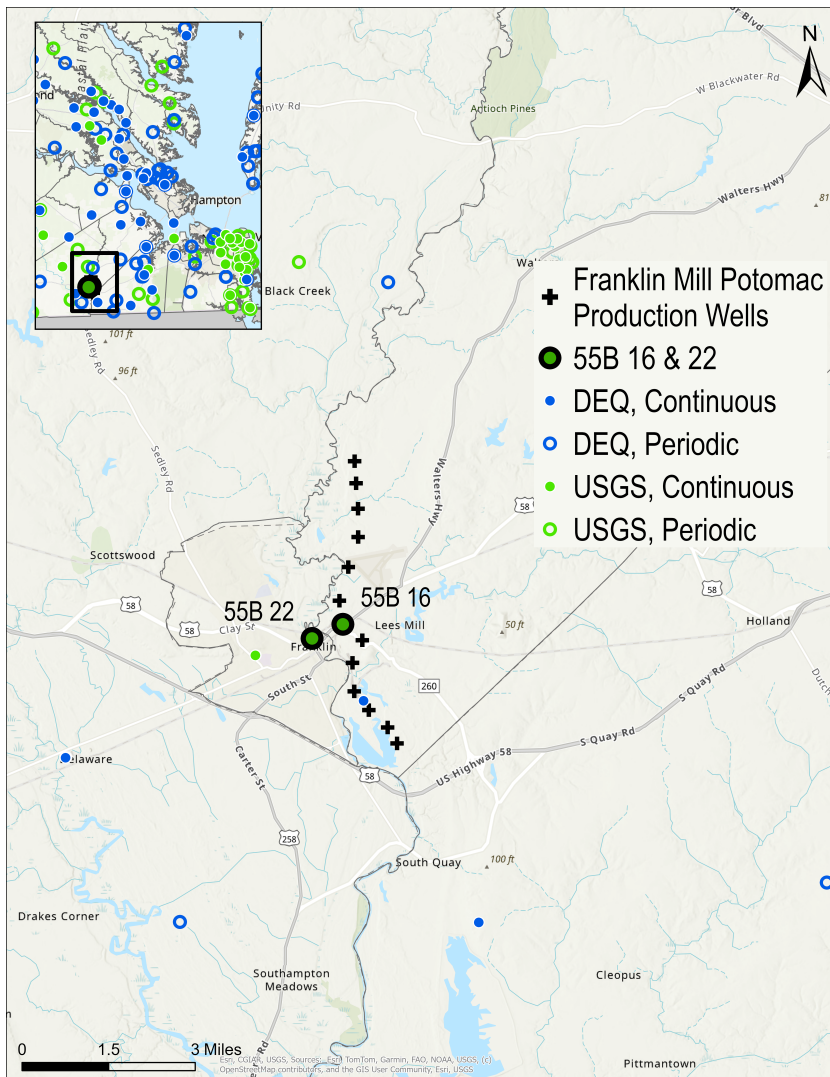
Together, the panels of Figure 24 illustrate how the overall total rate of groundwater withdrawal from the Potomac aquifer, and the Franklin Mill's withdrawal rate in particular, have fluctuated significantly over time. These changes have occurred in response to economic conditions, specific business decisions, and developments in Virginia's regulatory framework for groundwater management. Relevant historical events, noted for reference on the figure, include the following:

- **July 1, 1973:** Groundwater Act of 1973 (Va. Code § 62.1-44.83, et seq. [Repealed]), followed by regulatory implementation, including declaration of Critical Ground Water Areas;
- **July 1, 1992:** Ground Water Management Act of 1992,⁵⁶ followed by implementation of the current regulatory framework, including the Groundwater Withdrawal Regulations,⁵⁷ and the declaration of the Eastern Virginia GWMA and the Eastern Shore GWMA;⁵⁸
- **April 15, 2010:** Closure of Franklin Mill pulp and paper production;
- **March 2012** (approx.): Resumption of Franklin Mill groundwater withdrawal at a reduced rate, to support fluff pulp production at a repurposed portion of the mill;
- **January 1, 2014:** Expansion of the Eastern Virginia GWMA to include counties north of the York River and east of I-95, including the Middle Peninsula, the Northern Neck, and the strip between Fredericksburg and Alexandria; and
- **2014 to 2017:** DEQ's VCP Groundwater Initiative (GWI), described below and in Section 1.6.2.

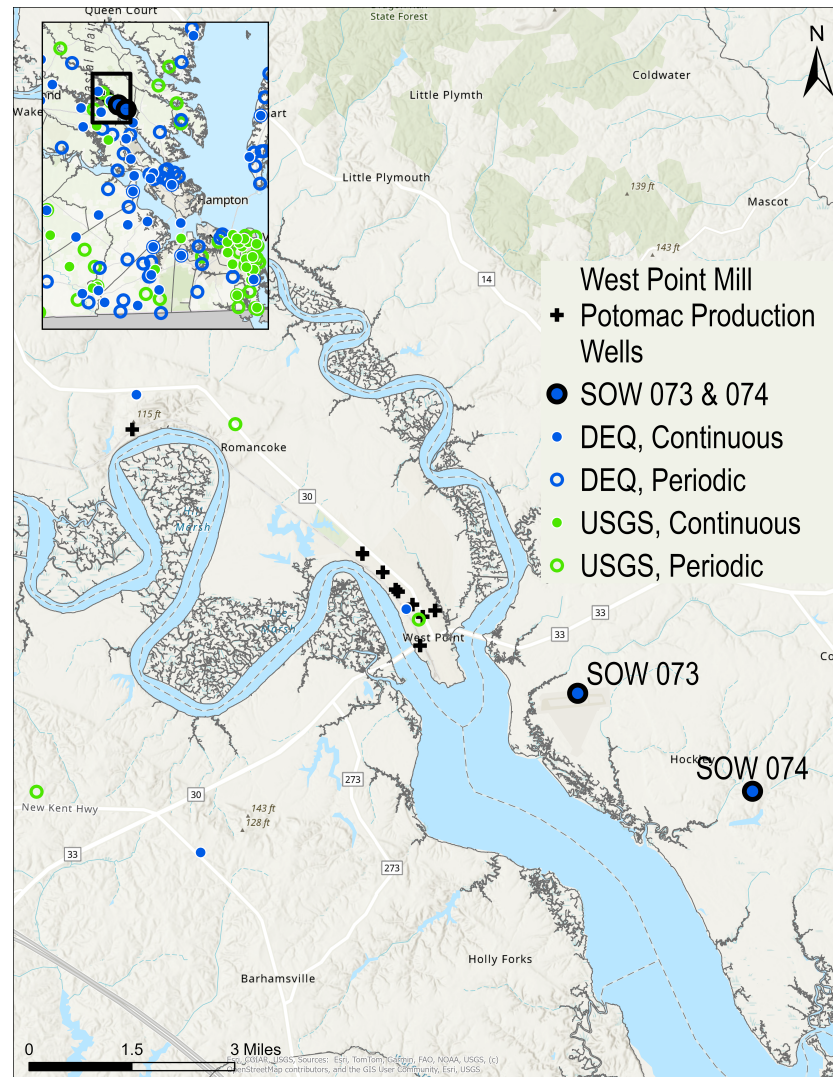
⁵⁶See VA. CODE ANN. § 62.1-254 et seq.

⁵⁷See 9 VA. ADMIN CODE § 25-610 et seq.

⁵⁸See 9 VA. ADMIN CODE § 25-600-20



(a) Franklin Mill wellfield.



(b) West Point Mill wellfield (additional nearby observation wells outside frame).

Figure 23: Paper mills' production wellfields and nearby DEQ-USGS observation wells, Potomac aquifer.

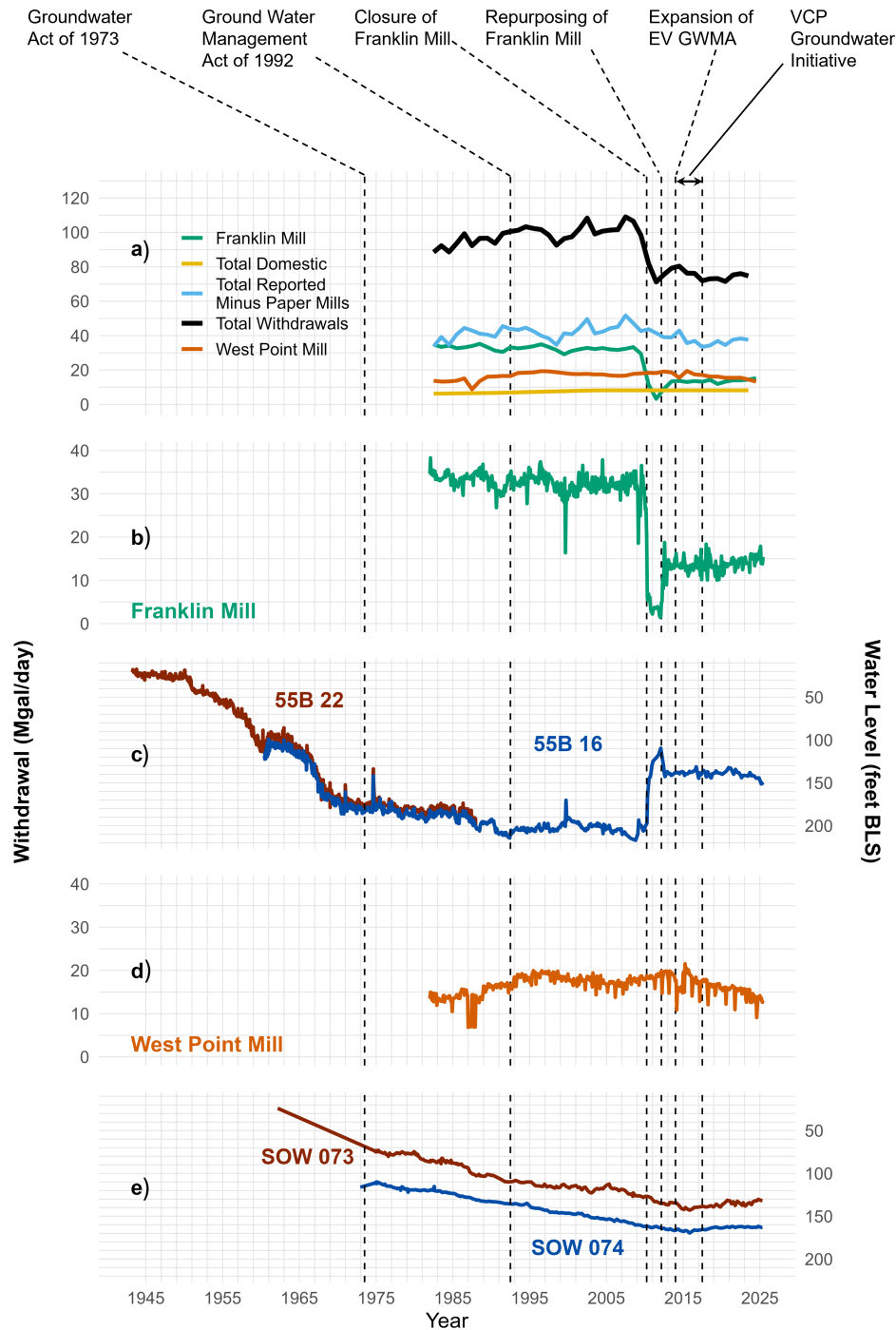


Figure 24: Potomac-aquifer withdrawals (Mgal/day) and their effects on water levels in nearby observation wells (feet BLS). Five time-series charts share a common x-axis: **a)** Total combined reported and estimated (unreported) domestic withdrawals from the Potomac aquifer, with subcategories plotted for comparison; **b)** Franklin Mill, monthly reported withdrawals; **c)** Water levels in observation wells 55B 16 and 55B 22, near Franklin; **d)** West Point Mill, monthly withdrawals; **e)** Water levels in observation wells SOW 074 and SOW 073, near West Point. Significant historical events are indicated by vertical dashed lines through all charts. See Figure 23 for wellfield maps.

2.2.2 Franklin Mill Closure

Key Point #5

The Franklin Mill closed in 2010 and partially reopened in 2012, causing a temporary rebound of groundwater levels that spread outward. From 2014 to 2017, DEQ undertook a special groundwater-management initiative. Consequently, the Potomac aquifer's annual overall groundwater deficit was reduced to nearly zero for about a decade. **Regional groundwater levels rose and broadly stabilized until about 2021. Rising trends then stalled and began to reverse as the temporary rebound spread, diminished, and was consumed by ongoing withdrawals across the region, including at the Franklin Mill. Under current conditions, groundwater levels throughout the Potomac aquifer are expected to enter a period of decline in the next five to ten years.** See also Section 2.3.2.

For the purposes of this section, the main event is the April 2010 closure of Franklin Mill operations, which caused a major stepwise reduction in withdrawal. From the earliest reported data in 1982 through 2009, the mill's overall average monthly withdrawal was about 993.2 Mgal (32.65 Mgal/day). In 2010, the reported monthly withdrawal fell sharply from 826.9 Mgal in March to 183.1 Mgal in May, a 78% reduction that occurred effectively overnight when the mill ceased operations in April. From May 2010 through February 2012, the mill's average monthly withdrawal was 111.7 Mgal (3.673 Mgal/day). This decrease of 29.0 Mgal/day represented an 89% reduction in the pre-2010 rate of withdrawal. Part of the mill was repurposed for the production of fluff pulp and resumed operational withdrawals in March 2012. From 2013 through 2024, the overall average monthly withdrawal was 416.2 Mgal (13.68 Mgal/day), or 42% of the pre-2010 amount. Starting around 2020, there occurred a gradual but consistent increase in Franklin Mill withdrawals. In 2024, the average monthly withdrawal reached 465.7 Mgal (15.31 Mgal/day), or 47% of the pre-2010 amount.

Between 2014 and 2017, DEQ undertook the VCP GWI to negotiate lower withdrawal limits in the permits of each of the top 14 groundwater users (Table 4). This effort was prompted by the recognition that VCP groundwater resources had historically been overallocated such that, if all users were to begin withdrawing their maximum permitted amounts, groundwater levels would be likely to resume long-term declines. Some of the negotiated permits, including the Franklin Mill's permit of 2017, included a tiered schedule of reductions in the permitted withdrawal limits. Under these reduced limits, the Franklin Mill's total reported withdrawal in 2024 amounted to nearly 96% of its permitted annual limit.

Since the Franklin Mill closure, overall reported use has remained relatively steady in the Potomac aquifer and in the larger VCP aquifer system. The maintenance of post-2010 gains in groundwater level can be attributed, at least in part, to the VCP GWI. However, the overall withdrawal rate in each of the years 2021–2023 was greater than in any of the years 2017–2020. Recent observational data suggests that groundwater levels across the Potomac aquifer mostly peaked or plateaued by 2021 and, in some cases, have begun to decline again (see Figure 25 and Section 2.3).

2.2.3 Local Hydraulic Effects

These large, fluctuating withdrawals induce regional effects that can be observed by the statewide groundwater observation well network. The USGS-operated observation well 55B 16 (USGS Site No. 364059076544901) is located adjacent to the main Franklin Mill property, and observation well 55B 22 (USGS Site No. 364047076552401) is located roughly 0.6 miles west (Figure 23a). These wells monitor the middle portion of the Potomac aquifer, where most of the mill's withdrawals are concentrated. The combined water-level record dates back to 1942, including discrete measurements that are typically collected on a quarterly frequency to the present day at 55B 16 (55B 22 has been out of service since 1987). This long-term record illustrates the general groundwater conditions in the Potomac aquifer through several historical phases. In the 1940s, water level was as high as 15.00 feet BLS. It may have been even higher in earlier days when flowing Potomac-aquifer wells were documented in southeastern Virginia (Figure 7). From about 1950 to the early 1970s, the water level declined steadily to about 180 feet BLS, with especially steep declines in the late 1960s, presumably driven by rapid industrial development.

During this period, the overall rate of groundwater-level decline was seven or eight feet per year. If the

decline had continued at that rate, then by around 1990 the water level would have reached the top of the Potomac aquifer, which is present at a depth of approximately 310 feet BLS near the Franklin Mill. A decline below the aquifer top would have begun **dewatering** the actual pore spaces of the confined aquifer, risking irreversible compaction of the aquifer sediments.

However, Virginia enacted its first groundwater law, the Groundwater Act of 1973, as shown on the figure. A period of moderate decline ensued, at an overall rate of roughly a foot per year. This continued until the early 1990s, when Virginia passed the Ground Water Management Act of 1992 that established the current regulatory framework. From 1992 to 2000, the water level rose gradually from about 210 feet BLS to 190 feet BLS (excluding an anomalous spike); from 2000 to 2009, the water level gradually declined to its historical low of nearly 220 feet BLS.

Starting in 2010, the water level in 55B 16 mirrored the major fluctuations in Franklin Mill withdrawals, outlined above. In fact, a comparison with the withdrawal data shows that, by 1999 or possibly earlier, the water level exhibited a strong sensitivity to, and negative correlation with, changes in Franklin Mill withdrawal. The 89% reduction in withdrawal that occurred around 2010 caused the water level to rebound by 107 feet, briefly returning to early-1960s levels of around 110 feet BLS. In 2012, the resumption of mill operations caused the water level to fall to about 140 feet BLS. It remained stable at that level until around late 2020, when the level began to decline at a consistent rate of almost three feet per year that has continued into 2025. This decline correlates with the rising mill withdrawals observed over the same period.

2.2.4 Regional Hydraulic Effects

Key Point #6

In the Potomac aquifer, hydraulic pressure effects travel tens of thousands of times faster than the typical flow of groundwater molecules through sediments. **Injections of water into the aquifer may yield a regional increase in groundwater levels with only local migration of the injected water molecules. However, regional water-level gains may dissipate rapidly when the injections cease.** This finding complicates the forecasting of groundwater levels that could result from aquifer replenishment, such as the Sustainable Water Initiative for Tomorrow (SWIFT). See also Section 2.6.1.

When the Franklin Mill's total withdrawal decreased in stepwise fashion, it caused a hydraulic perturbation that propagated over time across a wide region of the Potomac aquifer. To investigate this unusual event, DEQ examined hydrographs from 92 observation wells across the regional Potomac aquifer. This analysis expanded upon the approach of a preliminary study by the Hampton Roads Planning District Commission shortly after the mill closure occurred (Katchmark, 2012). Many of the hydrographs showed a characteristic inflection point that DEQ interpreted as the arrival of the Franklin Mill closure signal; the inflection point can be seen in selected hydrographs on Figure 25. In general, the greater the distance from the mill site, the later the signal arrived, and the less inflection occurred in the water-level plot. Wells with continuous monitoring data offered higher resolution and typically clearer inflection points. Wells monitored periodically by discrete measurement offered lower resolution (typically four per year) and less precise inflection points; for these wells, the arrival time was typically assumed to occur halfway between the dates of the two measurements that appeared to bracket the inferred inflection point. Hydrographs with excessive noise from nearby pumping wells were eliminated from consideration.

Ultimately, DEQ identified 55 hydrographs with inflection points representing the arrival of the Franklin Mill closure signal. For each well, DEQ computed the number of days that elapsed from April 15, 2010, to the arrival date and used GIS software to measure the distance between the Franklin Mill wellfield and the observation well. Figure 26 shows a plot of elapsed time (days) vs. distance from the wellfield (miles) for the set of all 55 wells and another plot for the subset of 21 wells whose **screens** were positioned in the middle zone of the Potomac aquifer, where the Franklin Mill withdrawals were concentrated. Linear regression was applied to each plot. The results from all zones of the Potomac aquifer had a fair correlation ($R^2 = 0.5991$) that was affected by several possible outliers. The estimated lateral propagation rate was about 5 days per mile (0.2 miles per day). The subset of results from the middle zone of the Potomac aquifer was cleaner, with a good correlation ($R^2 = 0.931$) and an estimated lateral propagation rate of 7.3 days per mile (0.14 miles per day).

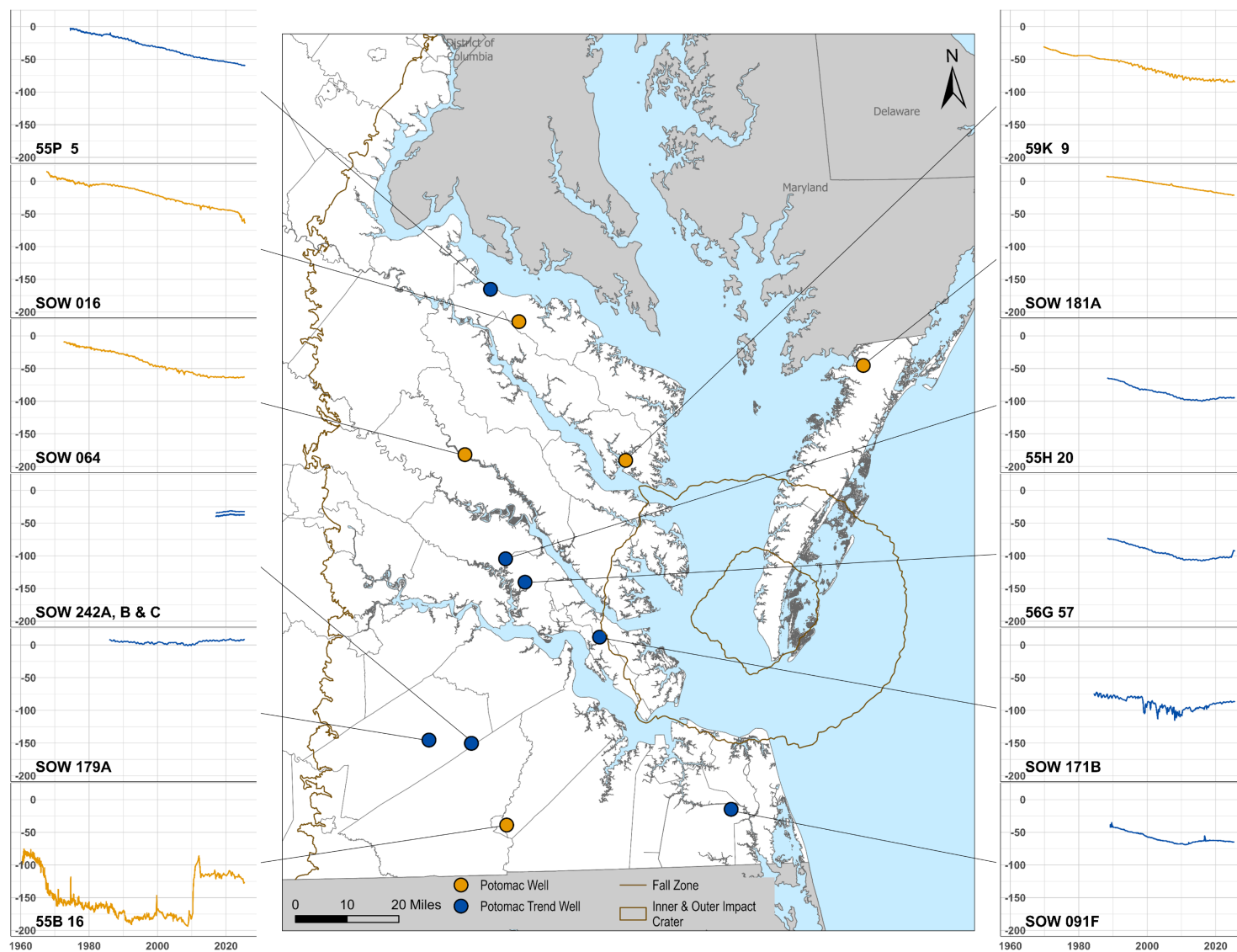


Figure 25: Hydrographs showing discrete, manually measured water levels in selected Potomac-aquifer observation wells, including locations selected for groundwater-level trend analysis (blue) and additional locations for comparison (orange), plotted on uniform *x*-axes of time (06/06/1960 to 08/29/2025) and uniform *y*-axes of elevation above sea-level datum (14.74 to -193.52 feet NAVD88) (USGS, 2024).

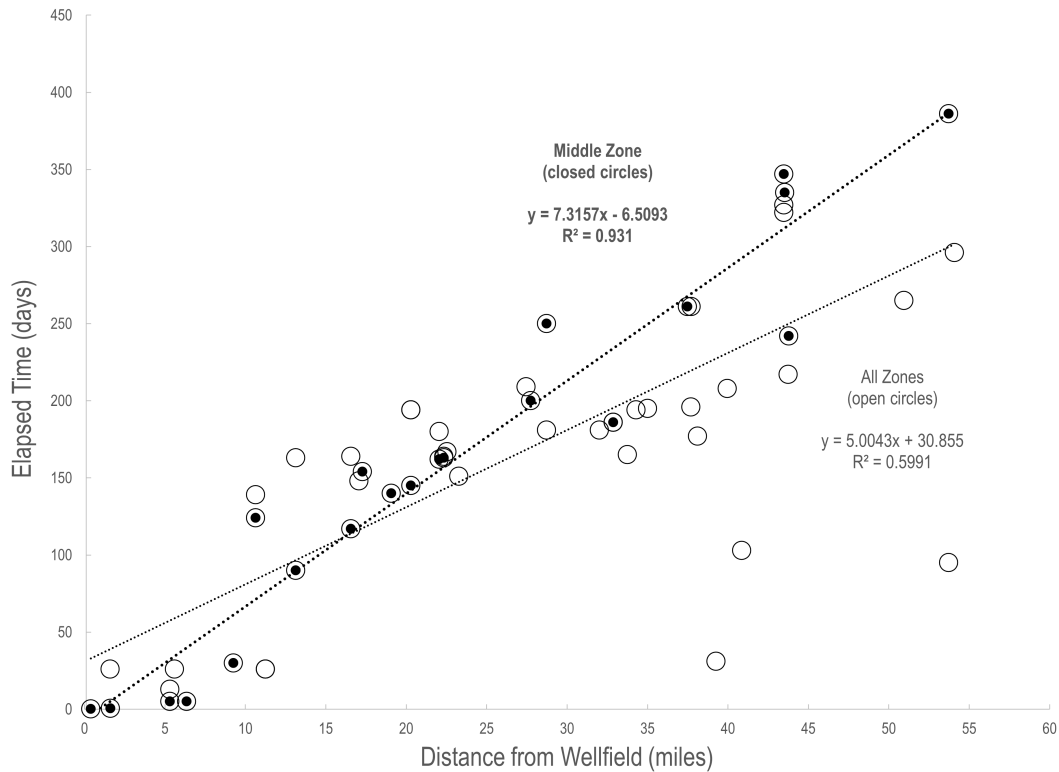


Figure 26: Elapsed time (days) between the stepwise reduction of Franklin Mill withdrawals and the arrival of the hydraulic effects at an observation well located at a known lateral distance (miles) from the production wellfield. Linear regression of data from wells screened in the middle zone of the Potomac aquifer (smaller, closed circles) yielded a stronger correlation than linear regression of data from all zones (larger, open circles).

In both plots, the last well to detect the signal, on day 386, was the Gloucester Landfill observation well, 58H 7 SOW 168B, located in Gloucester County, 54 miles from the Franklin Mill wellfield. At more distant observation wells, visual examination of the hydrograph could not reliably distinguish the arrival event from background variability in water level. Nevertheless, the groundwater-level trend analysis presented below suggests that the reduction in Franklin Mill withdrawals caused a general upward shift in water levels across a wide area of the VCP, possibly as far as Westmoreland County along the Potomac River.

A lateral propagation rate of 0.14 miles per day is equivalent to 740 feet per day or 270,000 feet per year. Importantly, this rate applies to the hydraulic pressure wave caused by the stepwise reduction of pumping, not to the flow of groundwater itself (i.e., movement of water molecules through the sediments). For comparison, [McFarland \(2013\)](#) reported two estimates of lateral groundwater flow rates in the Potomac aquifer: 10 feet per year in southeastern Virginia, where predominantly coarse-grained sediments have relatively high **hydraulic conductivity** (water permeability), and four feet per year farther north in Virginia, where finer-grained sediments have lower hydraulic conductivity. These estimates were based on ages of groundwater relative to the time of recharge, as determined by geochemical tracers ([Nelms et al., 2003](#)). The actual rate of groundwater flow varies in proportion to the **hydraulic gradient** (the slope of the **potentiometric surface**). This gradient is steeper in proximity to pumping centers, causing locally higher flow rates. However, in general, the gradient decreases rapidly with distance away from the pumping center (Figure 19), such that the values cited above may be generally representative of aquifer conditions. According to these numerical estimates, the hydraulic pressure wave caused by the Franklin Mill closure traveled through the aquifer system tens of thousands of times faster than the typical flow of groundwater through sediments.

To illustrate the regional pattern of propagation effects, Figure 27 maps the subset of middle-zone observation wells, with contours representing the elapsed time to arrival. The contours are consistent with an

approximately radial pattern of lateral propagation through the middle zone of the Potomac aquifer. The full data set (all zones) was too irregular to represent with contours. The observed irregularity was attributed to the additional complexity involved when the signal propagated through all three dimensions (vertical and lateral) of the **heterogeneous** Potomac aquifer.

These results showed how a large, stepwise increase in the local **hydraulic head** traveled across a broad region of the Potomac aquifer. This unusual event may offer an analog for future aquifer-replenishment projects designed to inject treated water into the aquifer to accomplish a similar increase in head. One such effort is the Sustainable Water Initiative for Tomorrow (SWIFT), a project of the Hampton Roads Sanitation District. Implications for this project are considered below, in Section 2.6.

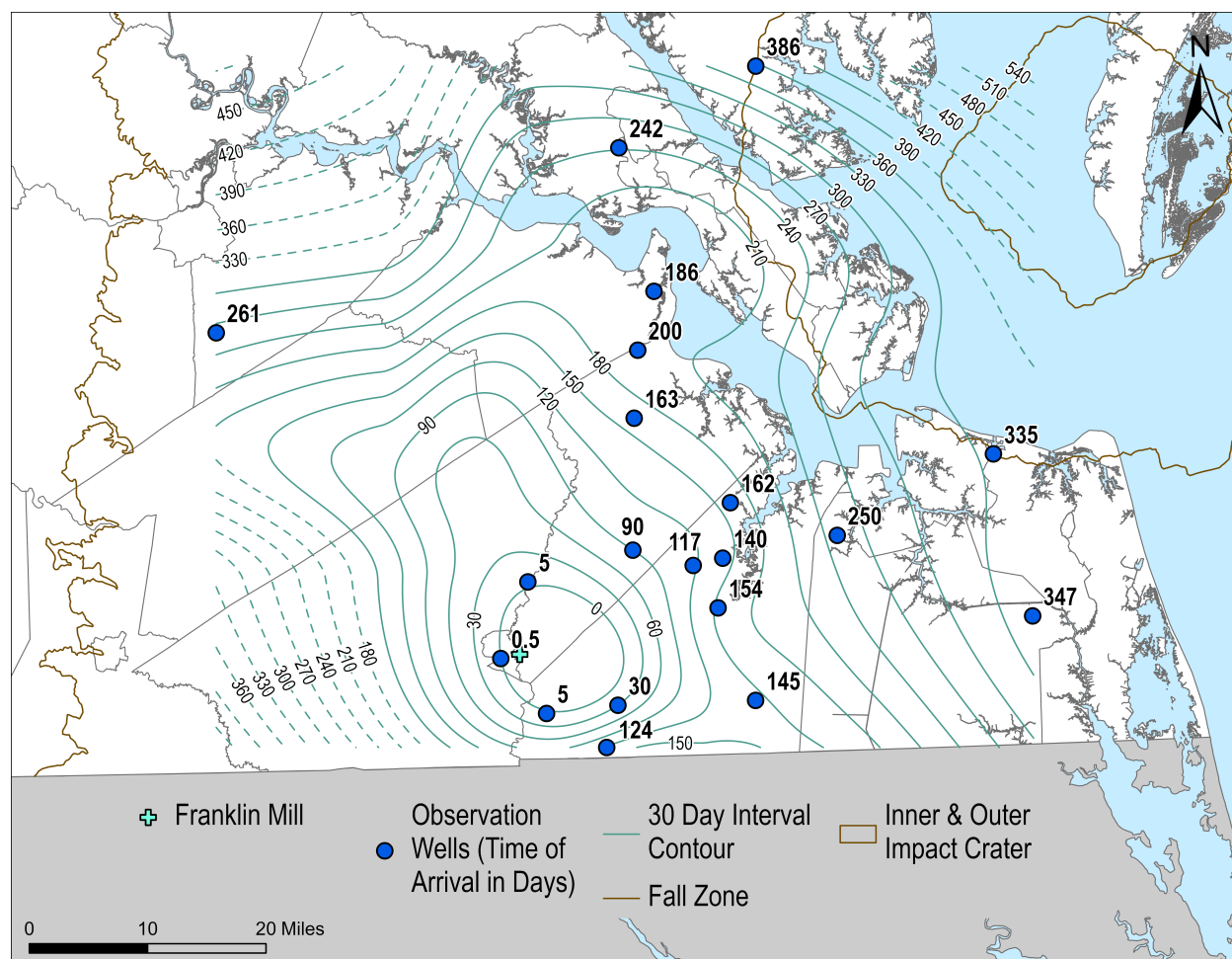


Figure 27: Contour map of elapsed time (in days) of middle zone Potomac aquifer pressure change due to Franklin Mill shutdown. Numerical values indicated elapsed time (days) between the stepwise reduction of Franklin Mill withdrawals and the arrival of the hydraulic effects at the indicated observation well, with contours representing 30-day intervals in elapsed time.

2.3 Groundwater-Level Trends

2.3.1 Method

For strategic planning and performance monitoring, DEQ developed a pilot method to analyze groundwater-level data for trends over time. The semi-automated method uses the [R software environment](#) to access continuous time-series data from the USGS's NWIS database ([R Core Team, 2023](#)). For a selected observation well, the R script computes (1) the annual minimum, maximum, and median depth to water (feet BLS) in that well for each calendar year over its full period of record, (2) the annual (year-over-year) change in the median depth to water, and (3) the running five-year average of that annual change, for each calendar year with sufficient data (four previous, consecutive years). DEQ uses the running five-year average as an indicator of trend: a positive value (increasing depth to water) indicates a declining water level in that well, and a negative value (decreasing depth to water) indicates a rising water level. In either case, the magnitude of the value represents an estimated rate of change (feet/year) in the water level over the five-year period ending in the indicated year.

For this pilot effort, DEQ selected nine wells to represent a variety of geographic locations and vertical positions within the confined Potomac aquifer (Table 8, Figure 28). At the time of their initial selection, all of the wells were continuously monitored, providing time-series water-level data over an extended period of record. However, continuous monitoring of SOW 091F ceased after 2020 because of changes in DEQ's field operations related to the COVID-19 pandemic emergency. For that well, from 2021 to 2024, it was necessary to compute annual median values from the much smaller set of periodic (usually quarterly) manual measurements collected by DEQ staff in the field. This procedure is noted in Table 8, which shows the 2024 trend results for each selected well. A smaller data set yields greater uncertainty, but the post-2020 results for SOW 091F were generally consistent with both the pre-2020 trend in that well and the general trend observed across all of the wells. Therefore, the 2021–2024 results computed from periodic measurements were included in the analysis.

Many more wells could conceivably be included in this type of analysis, but additional wells would introduce further complexity and labor. DEQ and USGS are currently exploring methods to automate a more comprehensive analysis of groundwater-level trends across Virginia's cooperative observation well network.

Table 8: Groundwater-Level Trends in Selected Potomac-Aquifer Observation Wells

USGS Local No.	Locality	Screened Interval (feet below land surface)	Change (2023 to 2024)	Trend	Running 5-Year Average	Trend
55P 5	Westmoreland County	451–466	1.525	Declining	0.998	Declining
55H 20	James City County	515–730 ²	-0.01	Rising	-0.34	Rising
56G 57	James City County	530–690 ²	-0.055	Rising	-0.336	Rising
58F 51 SOW 171B	Newport News City	820–830	-0.507	Rising	-0.589	Rising
53D 6 SOW 179A	Sussex County	460–470	-0.7	Rising	0.045	Declining
54D 7 SOW 242A	Sussex County	675–685	-0.14	Rising	-0.099	Rising
54D 8 SOW 242B	Sussex County	470–480	-0.155	Rising	-0.096	Rising
54D 9 SOW 242C	Sussex County	185–195	-0.315	Rising	-0.043	Rising
61B 13 SOW 091F ¹	Chesapeake City	1,370–1,380	0.54	Declining	0.392	Declining
Percentage of wells with rising water-level trend			–	78%	–	67%

¹ Values calculated from discrete (quarterly) manual measurements in the absence of continuous monitoring data since 2020.

² Multiple screens present within the overall interval shown.

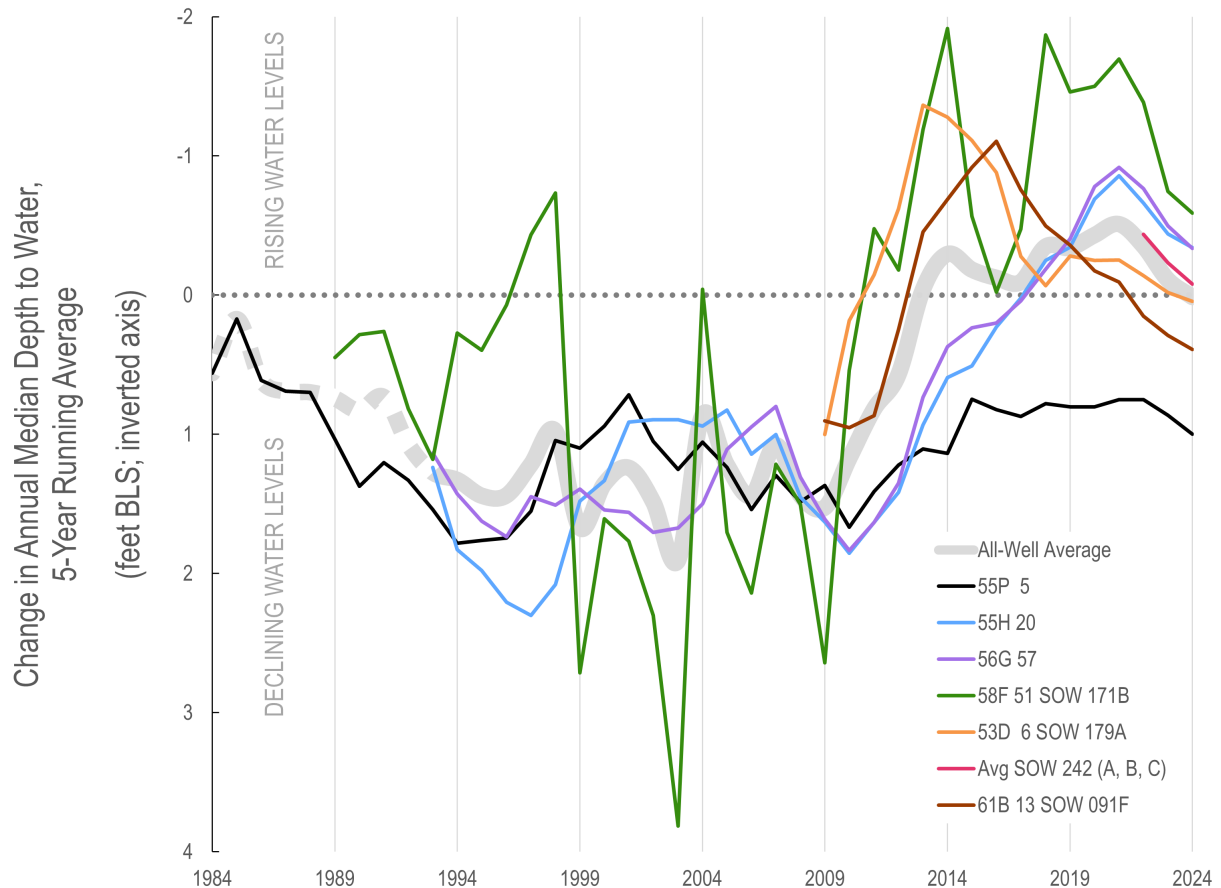


Figure 28: Groundwater-level trends in selected Potomac-aquifer observation wells, computed as the five-year running average of year-over-year change in annual median depth to water (feet below land surface). Note that a positive value is an increase in water depth, meaning a declining water level; the y -axis is inverted to represent rising levels in the upward direction. Colored lines are single-well trends except where noted. The thick gray line is an average across all wells with data at a given time; the dotted segment indicates greater uncertainty because of relatively sparse data.

2.3.2 Results and Discussion

Key Point #5 (repeated)

The Franklin Mill closed in 2010 and partially reopened in 2012, causing a temporary rebound of groundwater levels that spread outward. From 2014 to 2017, DEQ undertook a special groundwater-management initiative. Consequently, the Potomac aquifer's annual overall groundwater deficit was reduced to nearly zero for about a decade. **Regional groundwater levels rose and broadly stabilized until about 2021. Rising trends then stalled and began to reverse as the temporary rebound spread, diminished, and was consumed by ongoing withdrawals across the region, including at the Franklin Mill. Under current conditions, groundwater levels throughout the Potomac aquifer are expected to enter a period of decline in the next five to ten years.** See also Section 2.2.2.

Figure 28 plots the running five-year trend for each well over its full period of record. (The data table associated with this figure is available in the supporting Appendix A: Table A.3.) Note that some wells are older than others, which accounts for the varying length of the wells' individual plots on the x -axis (time in years). The y -axis measures the running five-year average of the annual (year-over-year) change in the

median depth to water (feet BLS); note that the y -axis is inverted so that negative values (rising water levels) appear in the upper portion of the line chart, with positive values (declining water levels) in the lower portion. Note also that the three collocated Airfield Pond wells, SOW 242A, B, and C, which target three different depth intervals within the Potomac aquifer, appear as a single, combined plot based on the average value of their nearly identical annual results.

The chart also features a plot of the overall average trend across all depicted wells, shown as a wide, gray line with smoothing. The statistical significance of the overall average trend was limited by the small sample size across a large region that is heterogeneous at multiple scales. However, the overall average offered a general illustration of changing trends across the system. Confidence in the value of the average trend increased with time over its 40-year domain, as the average incorporated additional data from new wells. The discussion below first focuses on this overall average trend, before considering the variations within and among individual wells.

The overall average trend showed a sequence of distinctive phases over time. Starting in 1984, the magnitude of annual groundwater-level declines increased steadily. This early phase could be an artifact of the sequential addition of new wells to the initially sparse dataset. Starting in the middle to late 1990s, following the passage of the Ground Water Management Act of 1992, the overall rate of decline stabilized and oscillated within the range from one to two feet per year. This steady, gradual decline was consistent with broadly observed patterns in hydrograph data from observation wells across the Potomac aquifer (Figure 25). Around 2010, the overall trend sharply reversed, such that the magnitude of decline rapidly diminished and became a rise in groundwater levels. This observation was consistent with observed hydrograph patterns in the period following the 2010 closure of the Franklin Mill, discussed above. From 2013 to 2023, the overall rate of water-level rise oscillated between approximately zero and 0.5 feet per year. In 2024, the overall average crossed slightly into a declining condition for the first time since 2012. This reflected a consistent pattern in the individual-well results, which uniformly shifted toward water-level declines since 2021.

In the context of this overall sequence, interesting patterns occurred within and among individual-well trends. The year-over-year change in median depth to water at SOW 171B, located in the City of Newport News, exhibited large short-term spikes in both directions, relative to those of all other individual wells in this analysis. Its year-over-year change ranged from -7.56 to 13.9 feet BLS, whereas all other values in the data set were within the range from -2.39 to 3.54 feet BLS. The observed spikiness may have been related to the pumping effects of the nearby Newport News Waterworks production wellfield or those of an unknown user, possibly amplified by proximity to the nearby low-flow boundary of the Chesapeake Bay impact crater (Figure 25). In any case, the five-year running average change for SOW 171B also exhibited a comparatively spiky profile in the line chart. It nevertheless followed the longer-term pattern of the system's overall average trend, shifting from a generally declining condition to a generally rising condition around 2010.

The profiles of individual-well plots in Figure 28 (and hydrographs in Figure 25) generally correlated with spatial position relative to the Franklin Mill in southwestern Isle of Wight County. Six of the observation wells in this analysis were located roughly along a transect running northward from the mill site: SOW 242A, -B, -C (approximately 18 miles from the mill site), 56G 57 (47 miles), 55H 20 (52 miles), and 55P 5 (104 miles). The three other wells were located farther off the transect: SOW 179A approximately 15 miles west of the transect (23 miles northwest of the mill site); SOW 171B approximately 19 miles east of the transect (41 miles northeast of the mill site); and SOW 091F approximately 43 miles almost due east of the mill site. Table 8 lists the wells in north-to-south order; the legend in Figure 28 matches this ordering.

Comparing the individual-well plots revealed that the hydraulic effects of the 2010 mill closure propagated generally from south to north over several years and that their magnitude diminished with distance. All of the wells responded rapidly to the stepwise reduction of the mill's withdrawals in 2010, but the timing and magnitude of the resulting peak rate of water-level rise in each well varied systematically with spatial position. SOW 179A and SOW 171B, the wells nearest the mill, peaked in 2013 to 2014. (The spiky profile of SOW 171B caused some uncertainty in identifying a single peak.) One might speculate that SOW 242A, -B, and -C would have responded similarly, given their proximity to SOW 179A, but those three collocated wells did not begin collecting data until 2017. SOW 091F, located about the same distance from the mill as SOW 171B but directly east (and screened 550 feet deeper in the Potomac aquifer), peaked in 2016, at a slightly lower maximum rate. 56G 57 and 55H 20, located in the same area of the York-James Peninsula, both peaked in 2021 at a yet slightly lower rate. Finally, 55P 5, located on the south bank of the Potomac River in Westmoreland County, never shifted into a condition of rising water levels; instead, the magnitude

of its annual decline moderated from 2010 to 2015 and stabilized at an ongoing decline of about one foot per year.

Six of the nine observation wells in this analysis exhibited rising water levels in 2024 (Table 8). However, as noted above, the individual-well plots in Figure 28 showed that, from 2021 to 2024, the annual trends for all nine wells shifted uniformly in the direction of water-level declines. For the wells with a trend of declining water levels, the rate increased. For the wells with a trend of rising water levels, the rate decreased—and for two of these wells, water levels began to decline for the first time since 2013. If this general shift were to continue on pace, all of the remaining wells in this analysis would likely enter a declining condition within five to 10 years.

2.4 Regional Groundwater Budget Analysis

2.4.1 Groundwater Budget Regions

For the purpose of analyzing groundwater resources in the VCP, the land area east of I-95 was divided into groundwater budget regions (GBRs). The eight GBRs are listed below and depicted on Figure 29. The regional groupings were based on a consideration of the Drought Evaluation Regions established by the “Virginia Drought Assessment and Response Plan” (DEQ, 2003), as well as geographic divisions, **geomorphologic** features, groundwater model domains, and groundwater resource demands. Regional boundaries were chosen to correspond with local government boundaries, and I-95 where applicable, to simplify discussion and analysis. While these boundaries are somewhat arbitrary, they generally correspond to regions of the Coastal Plain that share similar groundwater conditions.

- **Northwest Coastal Plain GBR:** King George County; the areas of Caroline County, Spotsylvania County, and the City of Fredericksburg located east of I-95; and the area of Stafford County located east of I-95 and within the domain of the Virginia Coastal Plain groundwater flow model (Heywood and Pope, 2009).
- **Northern Neck GBR:** Lancaster County, Northumberland County, Westmoreland County, and Richmond County.
- **Middle Peninsula GBR:** Essex County, Gloucester County, King and Queen County, King William County, Mathews County, and Middlesex County.
- **Middle James GBR:** The City of Hopewell; the areas of Chesterfield County, Hanover County, and Henrico County located east of I-95; and the areas of the Cities of Colonial Heights, Petersburg, and Richmond located east of I-95.
- **York-James GBR:** Charles City County, James City County, New Kent County, York County, and the Cities of Hampton, Newport News, Poquoson, and Williamsburg.
- **Chowan GBR:** Southampton County, Surry County, the City of Franklin; the areas of Prince George County and Sussex County located east of I-95; and the areas of Greensville County and the City of Emporia located east of I-95 and within the domain of the VCP groundwater flow model (Heywood and Pope, 2009).
- **Southeast Virginia GBR:** Isle of Wight County and the Cities of Chesapeake, Portsmouth, Norfolk, Suffolk, and Virginia Beach.
- **Eastern Shore GBR:** Accomack County and Northampton County.

Note that portions of the VCP aquifer system located in Fairfax County, Prince William County, and northeastern Stafford County were excluded from the regional groundwater budget analysis because they lie outside the domain of the VCP groundwater flow model that was used for the budget computations (Figure 29). Similarly, Tangier Island and the Virginia portion of Smith Island in the Chesapeake Bay were excluded from this analysis because, although they are part of Accomack County (Eastern Shore GBR), their primary freshwater aquifer is the deep Potomac aquifer, not the Yorktown-Eastover aquifer system that supports the

Eastern Shore. A separate, focused investigation would be required for evaluation of groundwater resources in either of these areas.

Groundwater budgets for the mainland VCP regions west of the Chesapeake Bay were computed using the 2023–2024 VAHydroGW-VCPM “reported use” simulation, and the groundwater budget for the Eastern Shore was computed using the separate 2023–2024 VAHydroGW-ES “reported use” simulation. Therefore, the groundwater budget results are based on the assumption of the “reported use” scenario that each withdrawal continues through the 50-year future simulation period (2024–2073) at the same annual volume that was reported to DEQ in 2023. A similar groundwater budget analysis that used the “total permitted” simulations would presumably yield different results.

2.4.2 Method

To quantify spatial variation in groundwater flow through the VCP aquifer system, DEQ engaged USGS to compute the groundwater budget for each of the eight geographic regions described above. The method and results are briefly summarized below. Complete details appear in a separate USGS open-file report (Pope et al., 2026).

The analysis began with the 2023 “reported use” simulations generated by Aquaveo using the VAHydroGW-VCPM implementation of the VCP flow model and the VAHydroGW-ES implementation of the Eastern Shore flow model (Section 1.6). USGS used the VCP flow model for the analyses of the seven regions west of the Chesapeake Bay and the Eastern Shore flow model for that separate peninsula. For each region, USGS applied the ZONEBUDGET software program to compute the groundwater budget (inflows and outflows) associated with the portion of each hydrogeologic unit present in the region (Harbaugh, 1990 and 2009). These segmented budgets were then grouped in various combinations to quantify the inflows and outflows within each region and, in the case of the mainland VCP, across all regions for (1) the unconfined surficial aquifer, (2) the deepest confined aquifer present in the model domain, and (3) the combined group of all intervening hydrogeologic units (to simplify a complex set of results).

This procedure focused on the primary aquifers of interest: the Potomac aquifer in the mainland VCP, and the Yorktown-Eastover aquifer system on the Eastern Shore. The analysis considered the three-dimensional (geographic and vertical) variation of flows in the VCP aquifer system over the entire historical period since 1890 and into the future through 2073. Analysis and discussion focused on two broadly representative moments in the time series of annual budget results:

- **2000**, representing the period after implementation of the Ground Water Management Act of 1992 and before the 2010 reduction in Franklin Mill withdrawals, and
- **2023**, representing current conditions, which have remained relatively stable since the hydraulic effects of the 2010 reduction spread across the region.

These events and periods are discussed fully in Sections 1.3 and 2.2, above.

2.4.3 Results and Discussion

Key Point #3 (repeated)

Major withdrawals, especially at paper mills near Franklin and West Point, have caused inland groundwater levels to decline below sea level, altering the predevelopment flow pattern in the VCP. Multiple lines of evidence show that groundwater now tends to flow inward from the margins toward the withdrawal centers and downward from higher to lower units in the VCP aquifer system. See also Sections 1.4.4, 1.5.2 (esp. Table 4), and 2.2 of report.

The results generally corroborated other findings, discussed above, that groundwater extraction from the VCP aquifer system has fundamentally altered groundwater flow from predevelopment conditions. The results included an estimate of the total yearly groundwater withdrawals in each GBR through the period of analysis (Figure 31). This figure again illustrates the rapidly increasing withdrawals that accompanied industrial development in the 20th century, followed by a period of more modest increases as Virginia

enacted groundwater management laws in 1973 and again in 1992 and implemented the attendant regulatory frameworks. The chart also shows the stepwise reduction that occurred in 2010 in the Southeast Virginia GBR, which includes Isle of Wight County where the Franklin Mill wellfield is located.

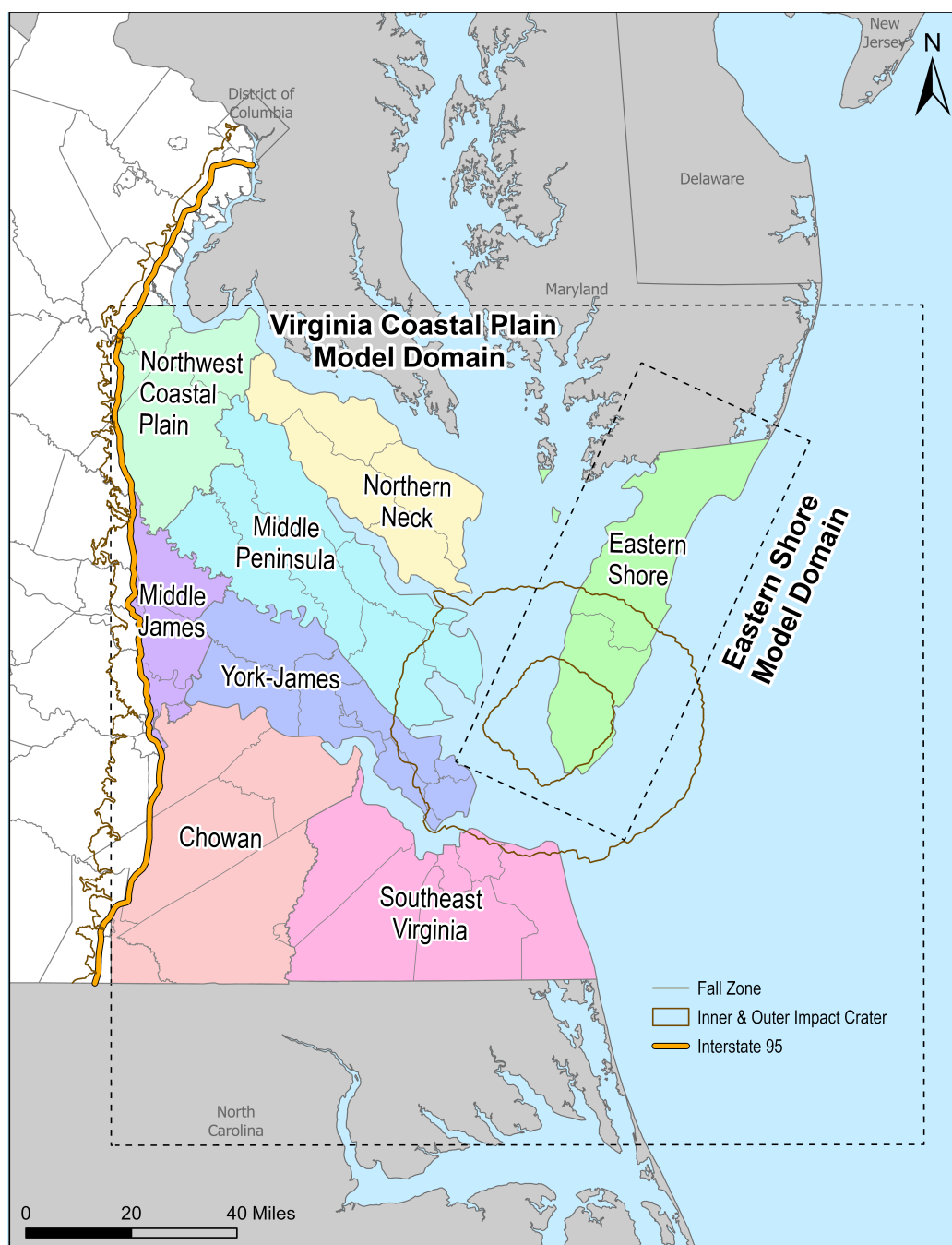


Figure 29: Groundwater budget regions delineated within the Virginia Coastal Plain for the purpose of analyzing groundwater resources. Key boundaries and features shown for reference (refer to Section 1.2.1).

Detailed results and discussion, including comprehensive numerical budgets, appear in the separate USGS open-file report (Pope et al., 2026). When reviewing budget results and the figures reproduced below, beware that the sign convention for groundwater **storage** change is reversed for consistency with the budget

computations. A net storage decrease (loss) is given a positive sign because it represents a source of water to the budget, making up for the deficit when total outflows exceed total inflows. Conversely, a net storage increase (gain) is represented with a negative sign.

The USGS report's key findings are summarized in the following excerpt, with added references to key figures that are reproduced below:

Groundwater budgets for the Virginia Coastal Plain show that groundwater flow is generally outward from the surficial aquifer to rivers and coastal water bodies and downward through a series of underlying aquifers and **confining units** to the Potomac aquifer, which is the deepest aquifer and the source of most groundwater withdrawals. Downward flow reaching the Potomac aquifer currently is estimated to be only 7% of the total net **infiltration** at the **water table** but makes up about 66% of inflows to the aquifer in Virginia. Lateral flows inward to defined groundwater budget zones in Virginia provide most of the remaining inflow to the Potomac aquifer. For several decades prior to 2010, high rates of withdrawal from the Potomac aquifer resulted in substantial decline in groundwater storage in the aquifer and in most overlying confined units. In the past 15 years, rates of withdrawal substantially lower than reported maximum have resulted in small net increases in groundwater storage in the confined aquifer system for most regions of the Coastal Plain in Virginia [Figure 30].

However, a relatively small rate of storage decline continues in the Potomac aquifer in areas outside of Virginia GBRs and in several of the hydrogeologic units overlying the Potomac aquifer. Under conditions when withdrawal rates were near historical maximums, close to 40% of total withdrawal from confined aquifers below the surficial were supplied by storage decline in the confined system, with about 84% of the storage decline from confined units other than the Potomac aquifer. Downward flow into the confined aquifer system has been influenced by pumping rates, with increased downward flow occurring during periods of higher withdrawal, such as the decade from about 1999 to 2009. Downward flow continues under current conditions, but flow rates are lower than in earlier decades with larger withdrawals. Even now, however, the downward flow induced by pumping is a large and important portion of groundwater budgets for confined aquifers, including the Potomac aquifer [Figures 32 and 33].

Geographically, groundwater flow in the confined part of the Virginia Coastal Plain is generally inward from perimeter regions of the Virginia Coastal Plain toward central regions with the largest withdrawal rates, including the Middle Peninsula, the York-James, and Southeast Virginia. Overall, small rates of ongoing storage depletion in the entire groundwater model, including areas outside of defined budget regions in Virginia, indicate loss of storage in the area beneath the Chesapeake Bay. This could mean inward movement of the salty groundwater interface, though that is not well quantified with the model zonation chosen for this study.

Groundwater budgets from the Virginia Eastern Shore model show that groundwater flow for the isolated aquifer system of that peninsula is generally outward from the surficial aquifer to coastal water bodies and downward into the confined Yorktown-Eastover aquifer system, which is the source of most withdrawals. Downward flow into the confined Yorktown-Eastover aquifer system is estimated to be only about 2% of total recharge and less than 9% of net infiltration, but makes up over 93% of all inflows to the aquifer. Decades of substantial but relatively consistent groundwater withdrawals have induced greater downward flow rates into the confined aquifer system and have resulted in loss of groundwater from storage. Currently, estimated storage loss accounts for slightly under 7% of withdrawals from the confined aquifer system. The current withdrawal rate from the confined Yorktown-Eastover system is near the highest reported rate for the Eastern Shore, which means that storage depletion is expected to continue at or near the current rate, even though groundwater levels appear to be relatively stable, with only slight declines in recent years [Figure 34]. Estimated groundwater flow rates upward from the confining unit underlying the Yorktown-Eastover system and small rates of inflow from coastal water bodies underscore ongoing concerns about up-coning and lateral **intrusion** of salty groundwater [Figure 35].

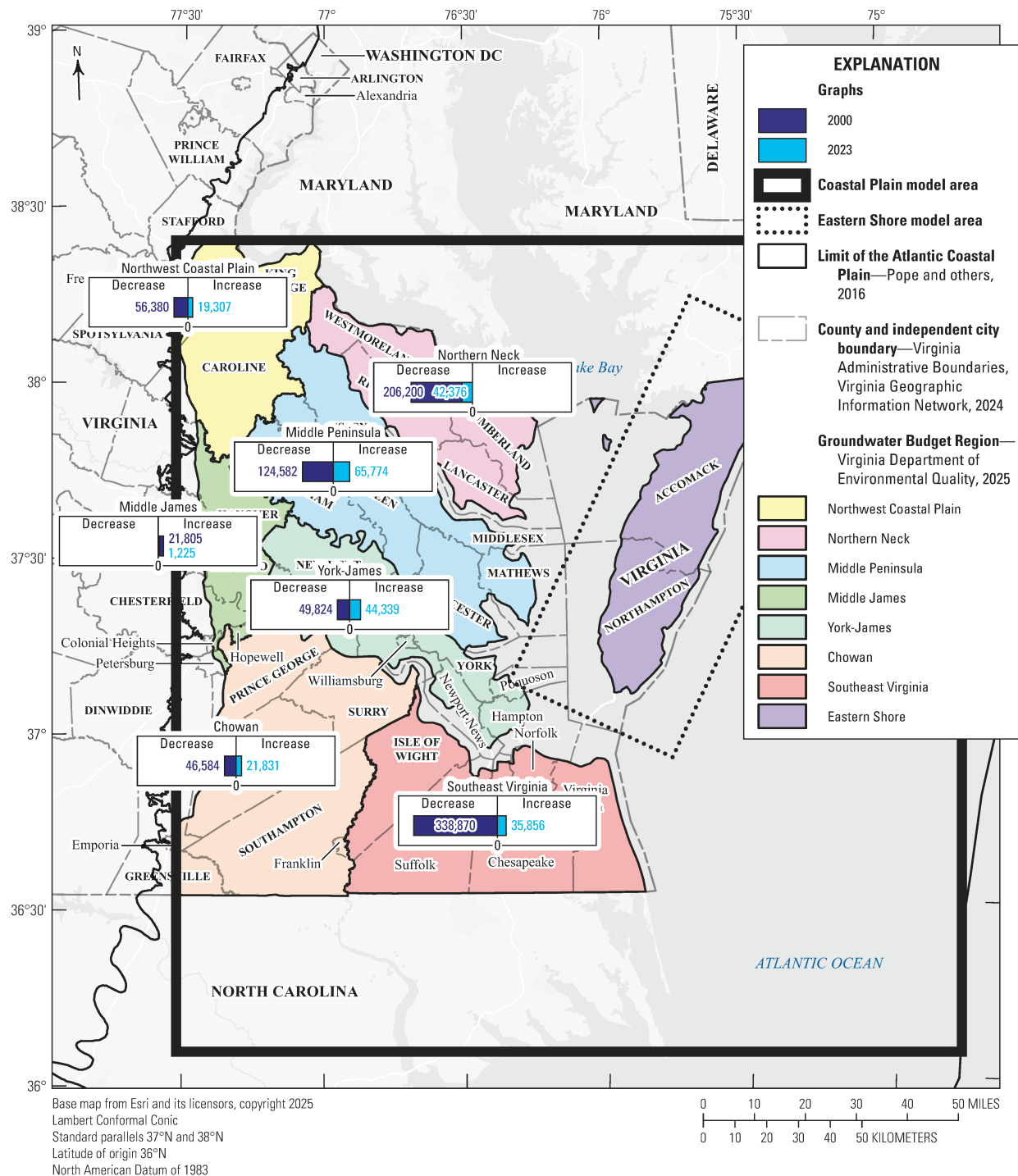


Figure 30: Comparison of groundwater storage rates in 2000 and 2023 in the Potomac aquifer for groundwater budget regions in the Virginia Coastal Plain model. Excludes Eastern Shore, where saline Potomac aquifer is unused for water supply. Values in cubic feet per day. Negative signs omitted for clarity. Reproduced from [Pope et al. \(2026\)](#).

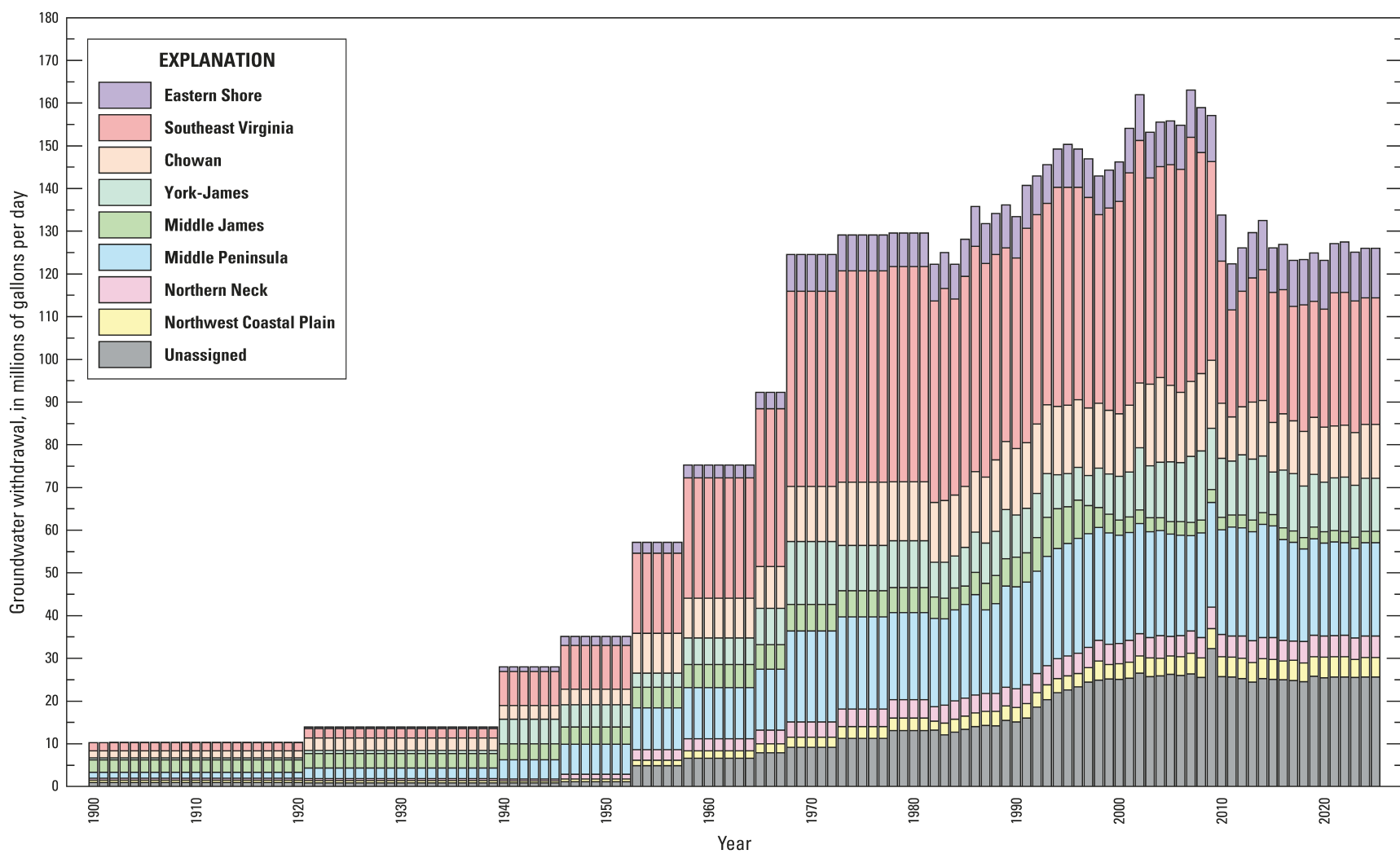


Figure 31: Simulated yearly combined groundwater withdrawals for the Virginia Coastal Plain and Eastern Shore groundwater models. Unassigned region includes model areas not delineated as a groundwater budget region. Reproduced from [Pope et al. \(2026\)](#).

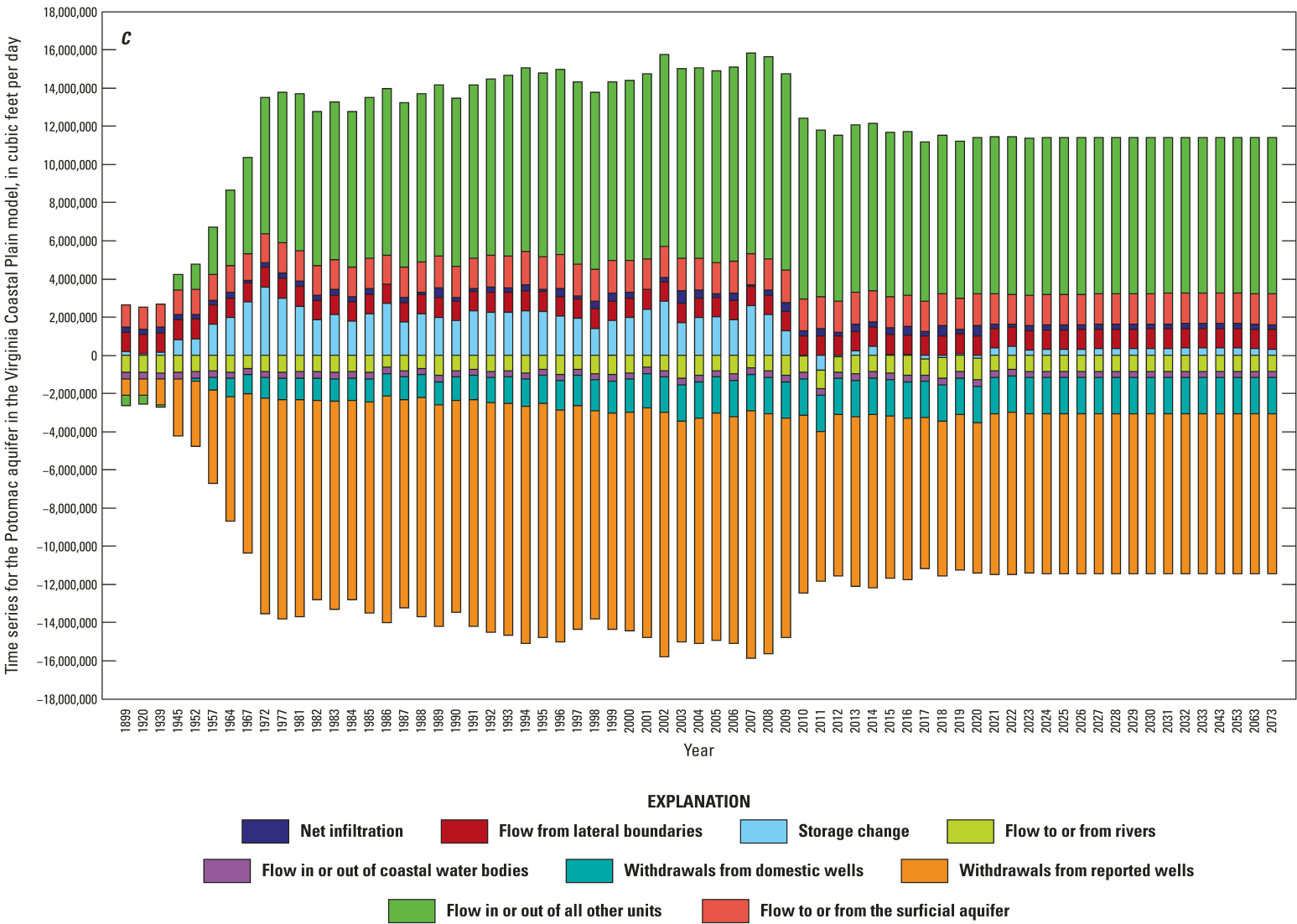


Figure 32: Simulated groundwater budgets for the entire Virginia Coastal Plain model area for all model time periods for the Potomac aquifer in the Virginia Coastal Plain model. Time periods for historical and future periods are multiple years in length. Values in cubic feet per day. Reproduced from [Pope et al. \(2026\)](#).

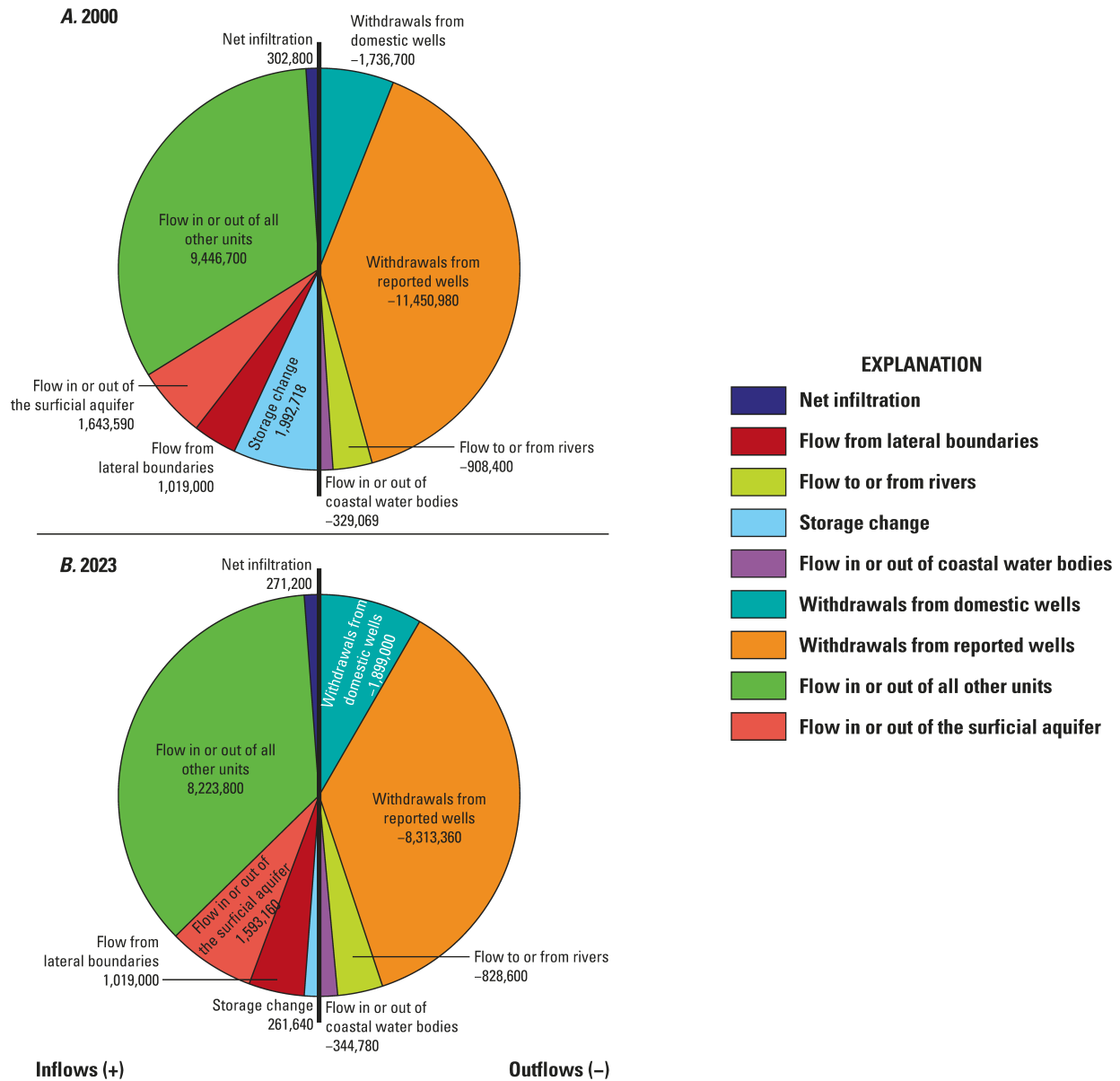


Figure 33: Simulated yearly groundwater budgets within designated Virginia groundwater budget regions for the Potomac aquifer in the Virginia Coastal Plain model for A, 2000, and B, 2023. Values in cubic feet per day. Reproduced from [Pope et al. \(2026\)](#).

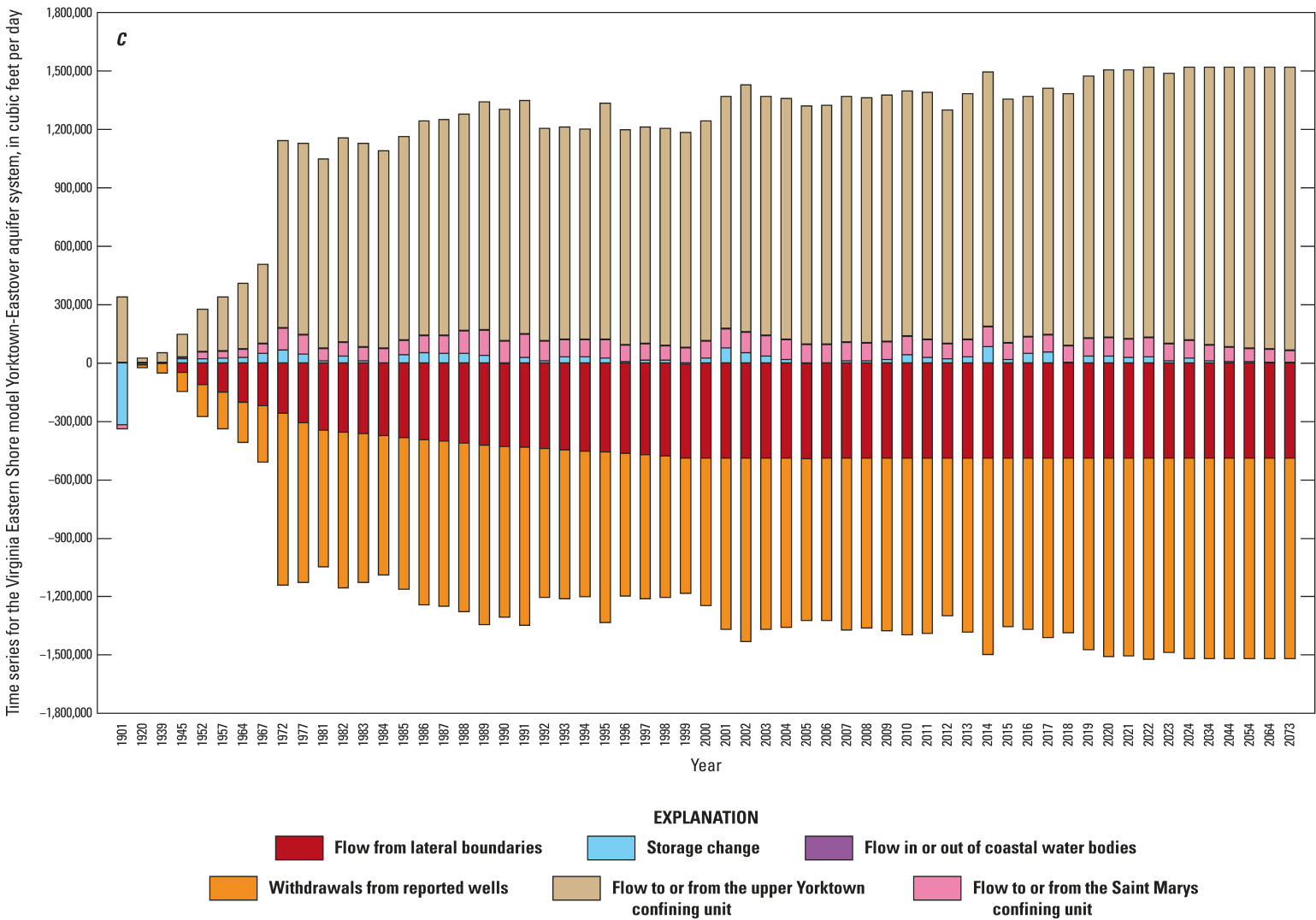


Figure 34: Simulated groundwater budgets for the combined Yorktown-Eastover aquifer in the Virginia Eastern Shore model for all model time periods. Time periods for historical and future periods are multiple years in length. Values in cubic feet per day. Reproduced from [Pope et al. \(2026\)](#).

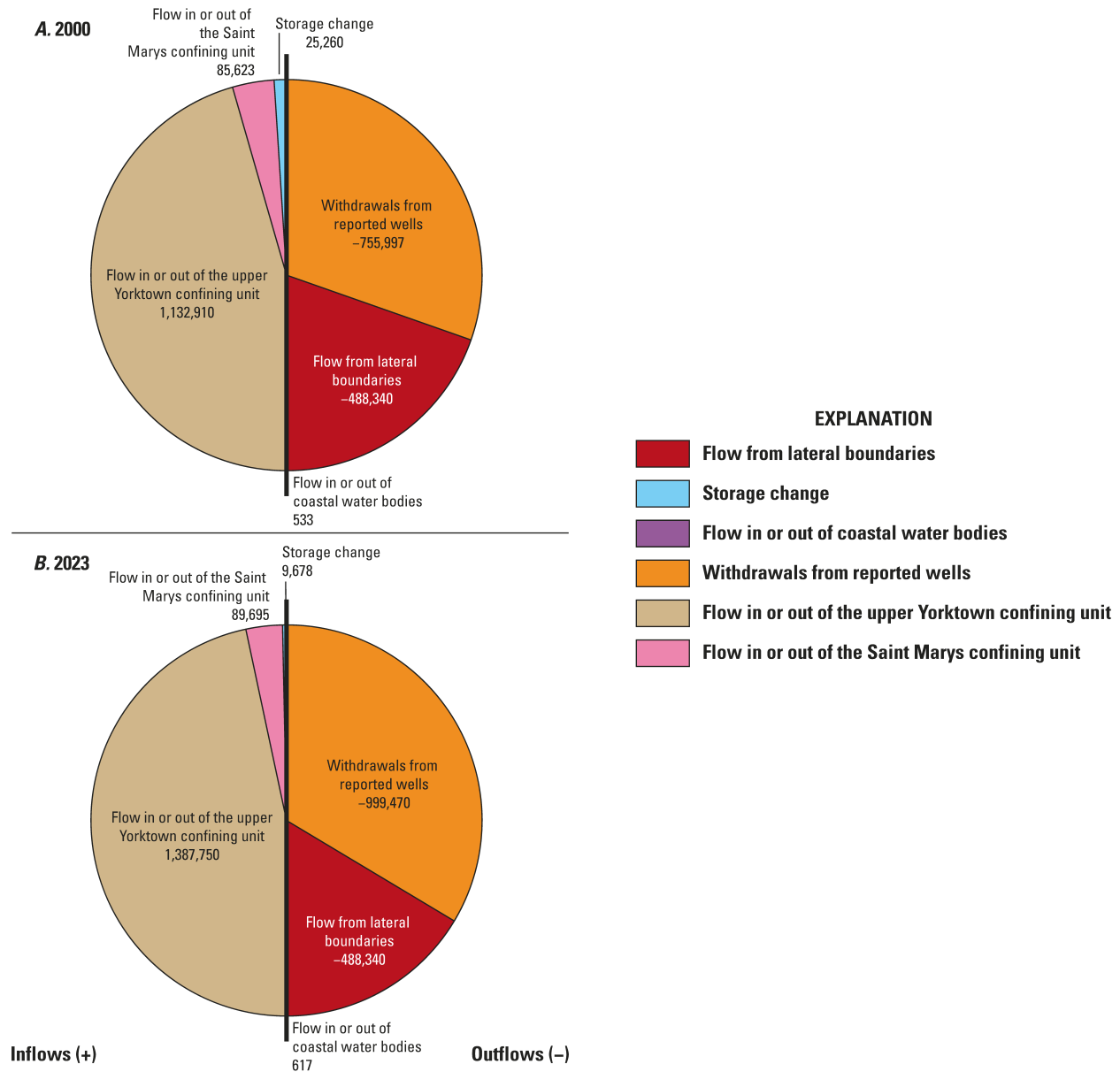


Figure 35: Simulated yearly groundwater budgets for the combined Yorktown-Eastover aquifer in the Virginia Eastern Shore model for A, 2000, and B, 2023. Values in cubic feet per day. Reproduced from Pope et al. (2026).

2.5 Projected Industrial Impacts

2.5.1 Overview of Existing Industries

As discussed in Section 1.5.2, industrial users reported a combined groundwater withdrawal of 35.6 Mgal/day, on average, in 2024. This amount accounted for over half of all reported groundwater withdrawals in the GWMA in 2024 (Table 3). Among the top 14 annual groundwater withdrawals in 2024, the two largest groundwater users in the GWMA were industrial facilities (Table 4). Three other industrial users were also among the top 14 facilities. These five facilities represented established industries, namely the production of paper, specialty chemicals, and poultry.

Figure 36 illustrates the spatial distribution of reported groundwater withdrawals in 2024 across the Eastern Virginia and Eastern Shore GWMA, both within the individual GBRs and in areas located outside the VCP groundwater flow model domain and the GBRs. The circles representing withdrawals are sized to correspond to the withdrawal volume, and the circles are color-coded to highlight industrial withdrawals. The reported groundwater withdrawals are summarized by GBR in Table 9.

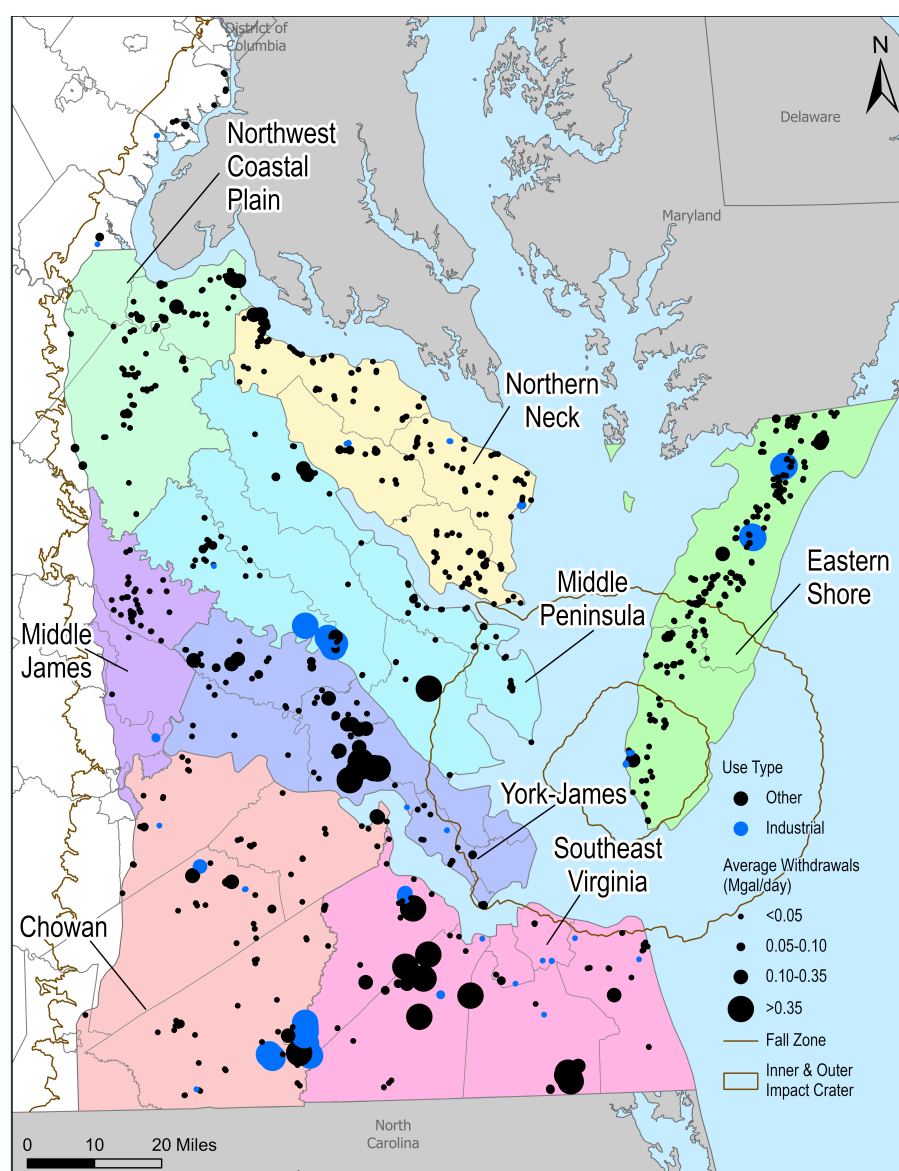


Figure 36: 2024 groundwater withdrawals in groundwater management areas, highlighting industrial withdrawals, with groundwater budget regions for reference.

Table 9: Groundwater Withdrawals by Budget Region

Groundwater Budget Region	2019–2023 Avg. (Mgal/day)	(Mgal/day)	2024 % Change from Avg.	% of Total
VCP area north of Fredericksburg (outside model domain)	0.180	0.199	10.633	0.296
Northwest Coastal Plain	1.901	1.889	-0.674	2.801
Northern Neck	2.117	2.032	-4.055	3.013
Middle Peninsula	18.262	15.803	-13.468	23.440
Middle James	0.622	0.568	-8.635	0.843
York-James	8.245	6.460	-21.653	9.582
Chowan	5.954	5.359	-9.985	7.949
Southeast Virginia	27.393	28.851	5.322	42.794
Eastern Shore	6.692	6.258	-6.486	9.282
Total (within model domain)	71.186	67.219	-5.582	99.704
Total	71.366	67.418	-5.547	100.000

2.5.2 Growth of Newer Industries Such as Data Centers

SJ 25 directs DEQ to “evaluate potential future impacts to the groundwater supply as a result of increasing groundwater withdrawals from newer industries such as data centers.” Virginia leads the nation and world in both number and density of data center facilities. In 2024, Virginia’s Joint Legislative Audit and Review Commission (JLARC) examined the industry’s economic impact, energy demand, zoning issues, infrastructure needs, and water usage within the Commonwealth. The JLARC study determined that while consumption was variable, 83% of individual data center facilities used about the same volume of water as an average large office building (6.7 Mgal/year) (JLARC, 2024). In an accounting of water use data provided by a subset of public utilities, the report showed that in Virginia, data center building water use values ranged from less than 0.5 Mgal/year to over 100 Mgal/year (JLARC, 2024). In regards to the information industry, Google is one of the only large data center operators that directly publishes water usage data. In 2024, Google’s Iowa data center, located in Council Bluffs, Iowa, reported the highest water use among its facilities, with withdrawals totaling approximately 1.0 billion gallons annually (2.74 Mgal/day). Google reported water usage information for four data centers in Virginia in 2024, consuming an average of 0.33 Mgal/day, with an average consumptive use factor of approximately 83% (Google, 2025).

Water Usage Effectiveness (WUE) is a metric used to quantify the amount of water required to cool a data center’s information technology (IT) equipment. It is calculated by dividing the total water consumption of the facility by the total electrical energy demand of the IT load, resulting in a value typically expressed in liters per kilowatt-hour (L/kWh). Lower WUE values indicate more efficient water use, as less water is needed to support the same IT energy demand. Following 2023, the average WUE across data centers was reported to range between 0.45 and 0.48 L/kWh (approximately 0.12 to 0.13 gallons/kWh; Shehabi et al., 2024). The County of Fairfax estimates that data centers use approximately 90 to 100 gallons of water per day per 1,000 square feet based on data from Fairfax Water (Fairfax County Department of Planning and Development, 2024). Based on this range, a data center consuming 3 million gallons of water per day would correspond to an estimated IT load of around 1,000 megawatts (MW), and an estimated size of 31.6 million square feet. In comparison, a more typical hyperscale data center campus with 100 MW of IT capacity would be expected to use approximately 300,000 gal/day and occupy about 3.2 million square feet.

The JLARC study also noted that water use by data centers varied based on the type of cooling system employed. Data centers utilizing evaporative cooling systems generally use more water, but less power compared to air-cooled systems (Siddik et al., 2021). New and emerging technologies for cooling, including water reuse practices, are increasingly being used by the industry to reduce dependence on local water supplies and to promote sustainability.

Water used at a data center facility is only part of the total footprint. Off-site water use—primarily for thermoelectric power generation—accounts for roughly 75% of total data center water consumption (Siddik

et al., 2021). In 2024, groundwater supplied only about 0.01% of power generation withdrawals statewide and most existing and planned data center capacity is located in public water supply service areas that primarily draw from surface water sources. In 2024, only about 7% of reported public water supply withdrawals in the Commonwealth were from groundwater sources.

Where data centers are using water, they are typically part of the distribution system of a larger public water supply system. As a result, their actual water usage is aggregated into annual water withdrawal reporting for the associated community water system. Where a data center seeks authorization to withdraw water from an independent, self-supplied source, a water withdrawal permit is likely required. In the GW-MAs, a groundwater withdrawal greater than or equal to 300,000 gallons in any month would be subject to permitting under the Groundwater Withdrawal Regulations⁵⁹, including the requirement for technical evaluation described in Section 1.6.3. Withdrawals of surface water may also require permitting under the Virginia Water Protection Permit Program Regulation⁶⁰. DEQ continues to pursue best practices for quantifying water withdrawals from data centers, especially as part of annual water withdrawal reporting and quantification in subsequent “Annual Water Resources Reports” (see Section 1.5).

There are numerous existing and proposed data center facilities within the Eastern Virginia GWMA, primarily around Richmond, Fredericksburg, and along the I-95 corridor, but none currently in the Eastern Shore GWMA (Piedmont Environmental Council, 2023). There is no publicly available comprehensive data source describing the groundwater-sourced portion of water withdrawals attributed to data centers. Virginia data center capacity is likely to double within the next 10 years (JLARC, 2024).

2.5.3 Simulated Withdrawal Evaluation Method

DEQ engaged its technical contactor Aquaveo, LLC, to perform a series of technical evaluations based on hypothetical withdrawals at selected locations across the VCP. As noted in the above section, withdrawals from the Potomac aquifer drive the overall dynamics of the confined aquifer system west of the Chesapeake Bay. Also, the Potomac aquifer is probably the VCP’s only aquifer that would be physically capable of yielding the volumes of groundwater under consideration here. For these reasons, all of the hypothetical withdrawals except one are designed to target the Potomac aquifer. That exception is on the Eastern Shore, where the Potomac aquifer is saline and groundwater users rely mainly on the shallow Yorktown-Eastover aquifer system for freshwater supply (Section 1.2.2).

For the eight GBRs described above, DEQ selected the centroid of each region as a generally representative location for a hypothetical withdrawal (Figure 37). DEQ also selected a ninth point, located at SOW 216 near Surprise Hill in Northumberland County, to represent a possible best-case scenario for a large-volume groundwater withdrawal. In this area of the lower Northern Neck, the Potomac aquifer is approximately 1,800 feet thick and the potentiometric surface is relatively high, offering relatively plentiful hydraulic head for withdrawal. The actual infrastructure in this area would not necessarily attract or support data-center or other large scale development, but the goal was to estimate the upper bound of groundwater availability in the VCP under the current regulatory framework and hydrogeological conditions.

For each of the nine locations, DEQ provided latitude and longitude coordinates, identified the target aquifer, and specified a withdrawal amount of 3 Mgal/day (1,095 Mgal/year) for technical evaluation according to the procedures described in Section 1.6.3, above. The value of 3 Mgal/day represents the upper end of published estimates of water usage by data centers that rely on evaporative cooling technology, as noted in the sections above. To provide a more realistic assessment of groundwater availability under current conditions, each technical evaluation also estimated the maximum volume that would meet the evaluation criteria for permitting at the specified location. Note that each technical evaluation considered the incremental effects of adding a single hypothetical withdrawal to the existing “total permitted” simulation; the analysis did not simulate the combined effects of multiple added withdrawals.

⁵⁹ See 9 VA. ADMIN CODE § 25-610

⁶⁰ See 9 VA. ADMIN CODE § 25-210

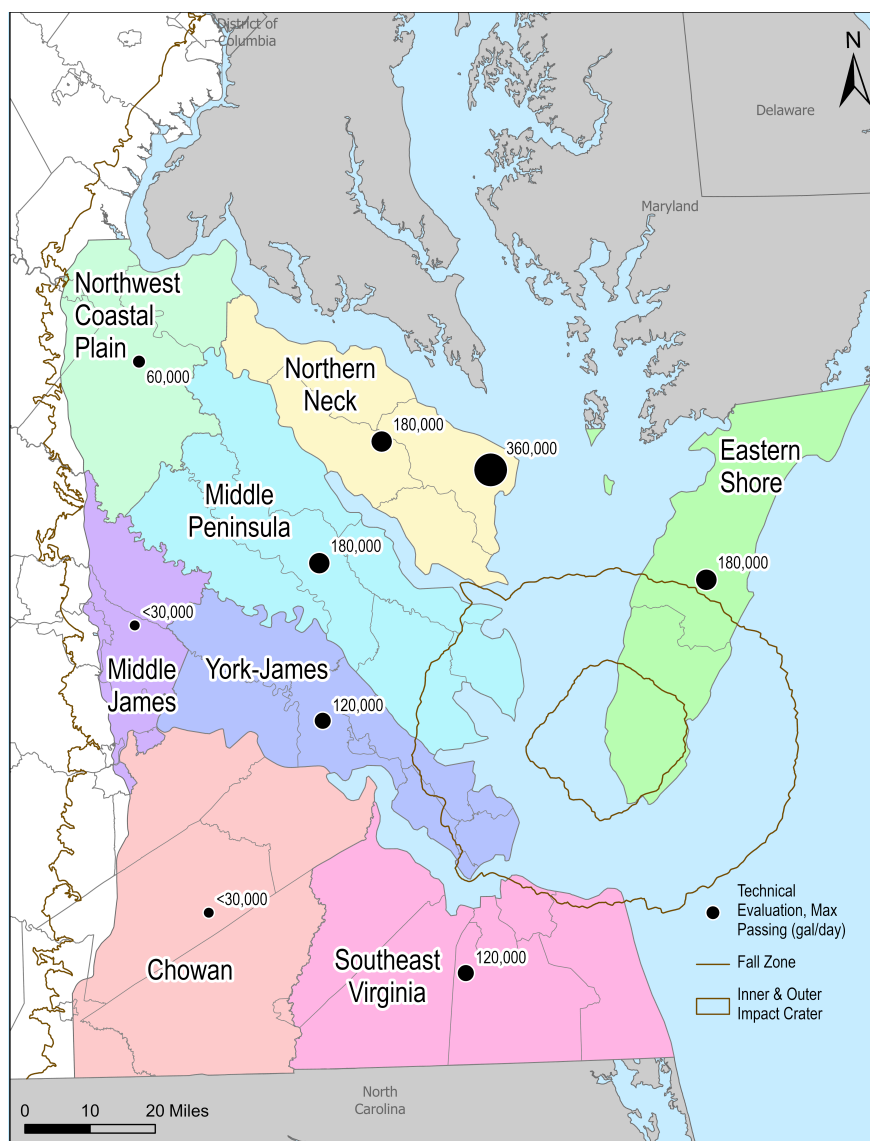


Figure 37: Maximum withdrawal (gal/day) projected to meet criteria for a groundwater withdrawal permit, with dot size scaled to volume and groundwater budget regions for reference.

For most of the technical evaluations, the withdrawal amount was apportioned evenly across the vertical column of model cells within the modeled Potomac aquifer. For the Southeast Virginia centroid, the withdrawal was apportioned evenly across all cells from the top of the modeled Potomac aquifer to a depth of 900 feet BLS, the estimated depth of the saltwater interface that would be avoided in a real withdrawal scenario. In the case of the Eastern Shore centroid in Accomack County, it was presumed that no single aquifer within the Yorktown-Eastover aquifer system would be capable of supplying the requested volume; instead, one-third of the withdrawal amount was apportioned across the model cells of each confined Yorktown-Eastover aquifer (Upper, Middle, and Lower). In all cases, the modeled pump intake was set at the top of the modeled source aquifer.

For the Surprise Hill withdrawal, two alternative scenarios were evaluated. The first was designed as a single-well withdrawal like the others targeting the Potomac aquifer. The second scenario divided the withdrawal into three 1-Mgal/day withdrawals, each at a separate well location—one at the same point as in the first scenario, one located a mile to the east, and one located a mile to the west. In this configuration, the three wells were located in three separate cells of the VAHydroGW-VCPM flow model. The purpose was

to evaluate whether a three-well field would allow for a greater total withdrawal volume than a single well. However, the results were identical, and the three-well configuration will not be discussed further.

2.5.4 Regional Withdrawal Capacity

Key Point #7

Under current conditions, the VCP aquifer system has limited capacity for significant new withdrawals. The estimated capacity for new withdrawals varies by region, from a maximum of 360,000 gallons per day in the eastern Northern Neck to less than 30,000 gallons per day in some western regions near I-95. Only the upper end of this range would support a significant new withdrawal for industrial use.

None of the hypothetical 3-Mgal/day withdrawals passed the evaluation criteria for permitting. The withdrawals located west of the Chesapeake Bay created large AOIs, extending as far as 91 miles from the well location (Table 10). These withdrawals generated AOIs in multiple aquifers, especially in the southern regions where each withdrawal created AOIs in five or six overlying aquifers. This result is consistent with the finding of the regional groundwater budget analysis that overall withdrawal from the Potomac aquifer is substantially offset by downward flux from overlying units (Section 2.4.3). The large AOIs intersected with many previously projected critical cells, and the withdrawals also created new critical cells, such that all of the withdrawals failed the 80% drawdown criterion. The technical evaluations also found that most of the withdrawals would cause a change in the simulated regional groundwater flow patterns, creating the potential for reduced groundwater quality. Details are available in Aquaveo's technical evaluation reports (Appendix B).

Table 10: Technical Evaluation Results for Hypothetical Withdrawals

Withdrawal Location	Locality	Withdrawal Aquifer	Maximum Extent of AOI (miles) ¹	Aquifers with AOI (bold = max. extent) ¹	Maximum-Passing Amount (gal/day)
Surprise Hill ²	Northumberland County	Potomac	75	Potomac , Aquia, Piney Point	360,000
Northwest Coastal Plain Centroid	Caroline County	Potomac	68	Potomac, Aquia	60,000
Northern Neck Centroid	Richmond County	Potomac	72	Potomac , Aquia, Piney Point	180,000
Middle Peninsula Centroid	King and Queen County	Potomac	90	Potomac , Aquia, Piney Point	180,000
Middle James Centroid	Henrico County	Potomac	66	Potomac, Aquia , Piney Point	<30,000
York-James Centroid	James City County	Potomac	91	Potomac , Virginia Beach, Aquia, Piney Point, St. Marys	120,000
Chowan Centroid	Sussex County	Potomac	77	Potomac , Virginia Beach, Aquia, Piney Point, St. Marys	<30,000
Southeast Virginia Centroid	City of Chesapeake	Potomac	78	Potomac , Virginia Beach, Pee Dee, Aquia, Piney Point, St. Marys	120,000
Eastern Shore Centroid	Accomack County	Yorktown-Eastover	8.2	Yorktown-Eastover , surficial	180,000

¹ For hypothetical volume of 3 Mgal/day.

² Two scenarios were run (1 well; 3 wells at 1-mile spacing), with the same result.

The withdrawal at the Eastern Shore centroid caused an AOI extending 8.2 miles from the well, in each of the Upper Yorktown-Eastover aquifer, the Middle Yorktown-Eastover aquifer, and the Lower Yorktown-Eastover aquifer, as well as a smaller AOI in the surficial aquifer. This withdrawal also failed the 80% drawdown criterion. In addition, the VAHydroGW-ES model simulated increases in chloride concentrations

of more than 250 (mg/L), plus the potential for pumping-induced **upconing** of relatively saline groundwater into the Upper Yorktown-Eastover aquifer. Details are available in the technical evaluation report (Appendix B.9).

The estimated maximum withdrawal amounts that were projected to meet the permitting criteria ranged from 360,000 gal/day at the relatively favorable Surprise Hill location (in Northumberland County) down to 60,000 gal/day at the Northwest Coastal Plain centroid (in Caroline County). For most other locations, the maximum-passing amount was 120,000 to 180,000 gal/day, with the higher values generally located farther north and east (Table 10, Figure 37). Of these estimates, only the high-end result of 360,000 gal/day at Surprise Hill was large enough to support the typical hyperscale data center described in the previous section (using approximately 300,000 gal/day to support 100 MW of IT capacity, and occupying about 3.2 million square feet). However, the Surprise Hill location is near Reedville at the Chesapeake Bay end of the Northern Neck, far from the areas where most development is occurring.

The Chowan centroid (in Sussex County) and the Middle James centroid (in Henrico County) happened to be located in critical cells predicted by the annual simulation, meaning that any AOI generated by their withdrawals would violate the 80% drawdown criterion. At these locations, even a withdrawal of 30,000 gal/day (1% of the requested 3 Mgal/day) was found to generate an AOI; lower withdrawal amounts were not simulated. Moving these two withdrawal locations to nearby non-critical cells would not substantially increase the estimated maximum-passing withdrawal. For regions in the western portions of the VCP, groundwater availability is quite limited, as indicated by the widespread areas of critical cells projected by the annual simulations (Figure 17).

2.6 Groundwater Levels: Summary

In this section, multiple lines of evidence provide a consistent narrative account of the historical development, current conditions, and projected future of groundwater levels in the VCP aquifer system. Since the onset of industrial development, major withdrawals from the Potomac aquifer have altered the regional hydraulic gradients such that groundwater now tends to flow from the periphery inward, towards the persistent cones of depression centered on Franklin and West Point. It also tends to flow from the shallower units downward, towards the Potomac aquifer where withdrawal rates are highest. These patterns are spatially associated with measurable land **subsidence** (Eggleston and Pope, 2013). They also raise the potential for landward migration of saltwater in the confined aquifer system (considered further in Section 3).

DEQ and USGS conducted analyses of historical withdrawals, observed water-level data, groundwater-level trends, and regional groundwater budgets, focusing on the Potomac aquifer. The results consistently indicated that the 2010 reduction in Franklin Mill withdrawals produced widespread but limited gains in the regional groundwater levels. These gains were preserved by DEQ's VCP GWI of 2014–2017, which negotiated a schedule of tiered reductions in the maximum annual withdrawal limit for the largest permitted groundwater users. Consequently, overall withdrawal rates and groundwater levels in the Potomac aquifer have remained relatively stable since about 2015. However, the analyses presented above suggest that the post-2010 gains have peaked and may be shifting towards a general condition of declining groundwater levels.

DEQ and Aquaveo simulated hypothetical major withdrawals (3 Mgal/day) at various points representing the GBRs within the VCP, including one location representing possible best-case hydrogeological conditions. None of the simulated withdrawals met the regulatory criteria to receive a permit. The maximum amount projected to meet the criteria ranged from 360,000 gal/day at the best-case location in Northumberland County to less than 30,000 gal/day (the lower limit of analysis) in some regions. Along with the other findings, these results suggest a VCP aquifer system that offers limited capacity to add major withdrawals. Under current conditions, it appears unlikely that a data center with evaporative cooling technology (or any comparable water user) would find a reliable, sufficient groundwater supply anywhere in the VCP. This is especially the case in the western portions of the VCP, near the I-95 corridor, where existing infrastructure is concentrated and where many existing data centers are located. In these regions, the aquifer system is relatively thin and groundwater availability is relatively low, approaching zero in some areas.

Overall, the results also demonstrate that the statewide groundwater observation well network is capable of monitoring groundwater levels and characterizing hydraulic events at multiple scales across the VCP aquifer system. The network's spatial coverage varies across the system, with a relatively high density of observation wells in the Potomac aquifer and in the southern half of the mainland VCP. Data-collection

frequency also varies. A denser, higher-resolution network would provide a higher-quality data set. However, each new well, especially those equipped with real-time monitoring instrumentation, requires additional operation and maintenance by DEQ (or USGS) staff. Any significant expansion of the network would require a proportional increase in staff and resources.

2.6.1 Implications for SWIFT

Key Point #6 (repeated)

In the Potomac aquifer, hydraulic pressure effects travel tens of thousands of times faster than the typical flow of groundwater molecules through sediments. **Injections of water into the aquifer may yield a regional increase in groundwater levels with only local migration of the injected water molecules. However, regional water-level gains may dissipate rapidly when the injections cease.** This finding complicates the forecasting of groundwater levels that could result from aquifer replenishment, such as the Sustainable Water Initiative for Tomorrow (SWIFT). See also Section 2.2.4.

The 2010 Franklin Mill closure event demonstrated how a stepwise reduction in local withdrawals caused a rapid increase in the local hydraulic head, which then propagated outward over time across a broad region of the Potomac aquifer (Section 2.2.4). This unusual event may offer an analog for future aquifer-replenishment projects, also known as managed aquifer recharge, or MAR. These projects are designed to accomplish a similar increase in the local hydraulic head, not by reducing an existing withdrawal but by injecting treated water into the aquifer.

One such effort is the Sustainable Water Initiative for Tomorrow (SWIFT), a project of the Hampton Roads Sanitation District. Major injection sites are under construction at the James River Treatment Plant in Newport News and the Nansemond Treatment Plant in Suffolk. At these sites, injections of highly treated water into the Potomac aquifer are projected to start in 2026 and 2029, respectively (Heisig-Mitchell et al., 2024). Full-scale SWIFT operations at the two sites will be designed to inject a combined total of approximately 50 Mgal/day into the Potomac aquifer. This injection rate has the same order of magnitude as the 29-Mgal/day reduction that occurred at the Franklin Mill in 2010. The similarity prompts a hypothesis that the injections will cause similar local hydraulic effects and that their regional effects will be observed over a similar geographic area and time period.

This working hypothesis has several implications. On the one hand, the results presented above suggest that sufficiently voluminous and consistent injections have the potential to raise groundwater levels across a wide region of the Potomac aquifer. On the other hand, the results also indicate that such groundwater-level gains would probably be sensitive to operational disruptions and other potential reductions in the injection rate. If the injections were suspended for any reason—technical, economic, or political—the groundwater-level benefits could prove transient, as has been observed since the initial gains that resulted from the 2010 Franklin Mill closure. These possibilities complicate and may preclude the assumptions that are necessary for modeling and prediction of groundwater levels 50 years in the future (see Section 1.6.3).

There have been attempts to use the current VCP groundwater flow model to explore possible effects of hypothetical injections into the Potomac aquifer, and the results have predicted potentially widespread benefits (DEQ, 2022; Frazier, 2022; Hampton Roads Sanitation District, 2022; Early and Mountjoy, 2024). However, the current model was not designed or optimized to simulate the regional effects of aquifer-replenishment operations. Calibrating a new model for this purpose would typically require at least 10 years of high-quality observational data collected during full-scale injection operations. Without this data set, there can be little confidence in predicting the aquifer system's response to an unprecedented stress condition. In addition, one hypothesized benefit of the SWIFT project is the reversal of withdrawal-induced compaction of the aquifer system. Measuring aquifer rebound and understanding its potential role in groundwater storage will require a complete network of **extensometers** with collocated groundwater observation wells. At the James River Treatment Plant injection site, the extensometer and wells are currently under construction (Section 1.4.4). DEQ's recommendation is to collect a sufficient record of groundwater-level data and aquifer-compaction data before attempting to simulate aquifer replenishment for the purposes of groundwater management. In the meantime, as the initial effects of SWIFT injections are monitored, any measured benefits can be considered in permitting decisions.

3 Groundwater Quality

3.1 Background

Understanding the processes controlling the regional groundwater chemistry in the VCP **aquifer** system, particularly the distribution of salinity, is vital to the sound long-term management of the groundwater resource. Recent trends of increased groundwater withdrawals within areas of elevated salinity raise the possibility of additional local or regional effects on the salinity distribution. Analyses presented in this section generally confirm and expand the current understanding of the processes controlling the distribution of salinity in the VCP.

As discussed in previous sections, extensive and sustained withdrawals from the **confined** aquifer system of the VCP have resulted in declines in regional groundwater levels. As a result, **potentiometric surfaces** have declined below sea level and effectively reversed the regional **hydraulic gradient** from seaward to landward. This reversal has disrupted the natural freshwater/saltwater balance along the saltwater-transition zone and created the potential for regional saltwater **intrusion** (Harsh and Lacznia, 1990).

The saltwater-transition zone is a dynamic boundary, with a spatial distribution shaped by geologic structure, freshwater flow, relative sea-level rise, and human activity. Under natural conditions, freshwater from the western recharge areas flows eastward and pushes against the seawater at the coast. The shift in hydraulic gradient from long-term withdrawals has effectively reversed this process, raising the possibility that coastal seawater is pushing inland against freshwater from the west.

The system is further complicated by features of the VCP that impart some control on the distribution and movement of the saltwater-transition zone. Pumping can exert a strong localized influence on water quality by allowing saltwater to be drawn towards the pumping center either laterally (intrusion) from regions of elevated salinity or vertically (**upconing**) from denser, deeper, saltier layers (Heath, 1983). These pumping effects are most notable in proximity to the saltwater-transition zone, especially coastal areas.

A zone of groundwater with higher-than-expected salt concentrations has been recognized and located approximately 50 kilometers west of its expected position. This zone was termed the “inland saltwater wedge” (Cederstrom, 1943). Similarities between the configuration of the inland saltwater wedge and the western margin of the Chesapeake Bay impact crater suggest that the impact and associated geologic structures play a role in the shaping of the saltwater wedge and its response to withdrawal stresses. Hydraulic boundaries associated with the impact structure causes flow to diverge laterally to either side of the crater, leaving unflushed seawater trapped at depth along the outer rim of the crater.

In shallower aquifers, the saltwater-transition zone is also affected by tidal processes, as saltwater extends upstream in major estuarine rivers throughout the VCP. Additionally, rising relative sea level will increase the potential for landward migration of the saltwater-freshwater interface.

The chemical composition of groundwater changes as it permeates through the VCP sediments. As water moves eastward, chemical weathering and ion exchange with clay minerals and glauconite alter the chemistry. Ultimately these transformed waters mix with seawater along the saltwater-transition zone. Regional trends in groundwater quality were first recognized by Sanford (1913), who noted that mineralization (total ions) of water increased towards the southeast. He reported that this increase was not directly a result of increased depth or the chemical composition of the strata. Fundamentally, he had identified the saltwater-transition zone. Building on the work of Sanford, Cederstrom published a series of reports that further delineated and described the groundwater quality of the VCP (Cederstrom, 1939; 1941; 1943; 1945; 1946a; 1946b). Following Cederstrom, most groundwater quality studies have been of limited geographic extent with very few encompassing the entirety of the VCP. The works of Focazio et al. (1993) and McFarland (2010) have provided perhaps the best synopsis of the recent VCP groundwater chemistry status and trends. The latter publication serves as the baseline of groundwater quality on which the VCP groundwater system is modeled and on which this report builds.

3.1.1 Processes and Distribution of Groundwater Quality

With a few exceptions, the water-quality parameters of pH, temperature, and dissolved oxygen are consistent throughout the **hydrogeologic** units comprising the VCP. The pH and temperature in most hydrogeologic units are very close to both their mean and median values, with pH values slightly above 7.1 and temperature consistently in the middle to upper teens in degrees Celsius. The pH in most hydrogeologic units

generally falls between approximately 7 and slightly above 8. This narrow range is associated with congruent dissolution of calcium-magnesium carbonates. In the surficial aquifer and the basement bedrock, pH is typically closer to 6, probably reflecting meteoric water (precipitation) and associated recharge. Dissolved oxygen is predominantly below 1 mg/L in most hydrogeologic units, due to oxygen consumption by chemical weathering processes. The exception is the surficial aquifer, where dissolved oxygen concentrations are closer to 3 mg/L due to atmospheric contact. The few extreme individual values for pH, temperature, and dissolved oxygen may be artifacts of sample collection, analysis, or reporting. Conversely, the extensive ranges observed in specific conductance and total dissolved solids are likely indicative of significant variations in total ion concentrations.

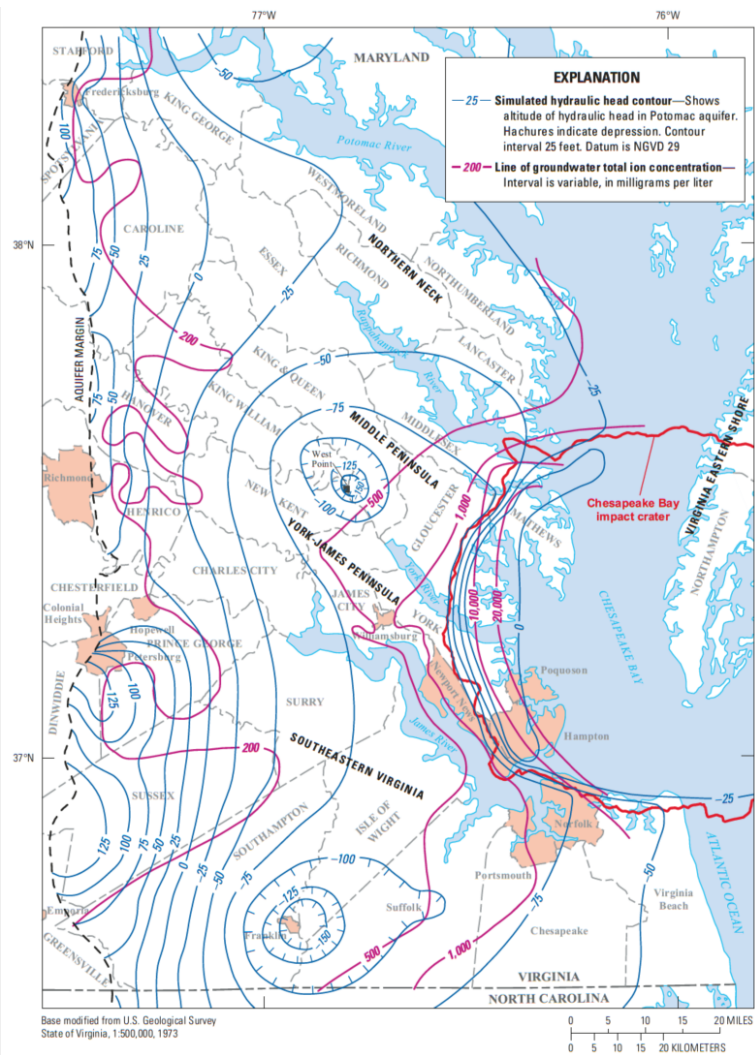
Back (1966) advanced the concept of hydrochemical **facies** (a body of groundwater with distinctive characteristics), which describes the evolution of groundwater composition along regional flow paths throughout the Northern Atlantic Coastal Plain. These trends in groundwater quality are predominantly influenced by variations in the concentrations of major ions, which constitute the primary chemical composition of groundwater by weight or concentration. In this context, the major ions include the cations calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+), and the anions bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), sulfate ($H_2SO_4^{2-}$), and chloride (Cl^-). Principally, the groundwater in the VCP can be defined by predominant ion-type, based on 50% or greater of a particular cation, anion, or ion pair. Designated cation types are the pairs of calcium plus magnesium ($Ca^{2+}+Mg^{2+}$) and sodium plus potassium (Na^++K^+). Anion types are bicarbonate plus carbonate ($HCO_3^-+CO_3^{2-}$), sulfate ($H_2SO_4^{2-}$), and chloride (Cl^-). The ion pairs calcium plus magnesium and bicarbonate plus carbonate are associated by chemical weathering of subsurface sediments, sodium plus potassium by cation exchange and chloride with saltwater mixing. These transitions can be visualized through total ion concentrations. Figure 38a illustrates the increasing ion concentrations through the Potomac aquifer. The 500 and 1,000 mg/L total ion **iso-concentration** contours (lines of equal concentration) are roughly coincident with the distribution of the 250 mg/L chloride concentration depth contours shown in 38b.

Most of the groundwater samples are categorized as one of three major ion types (McFarland, 2010):

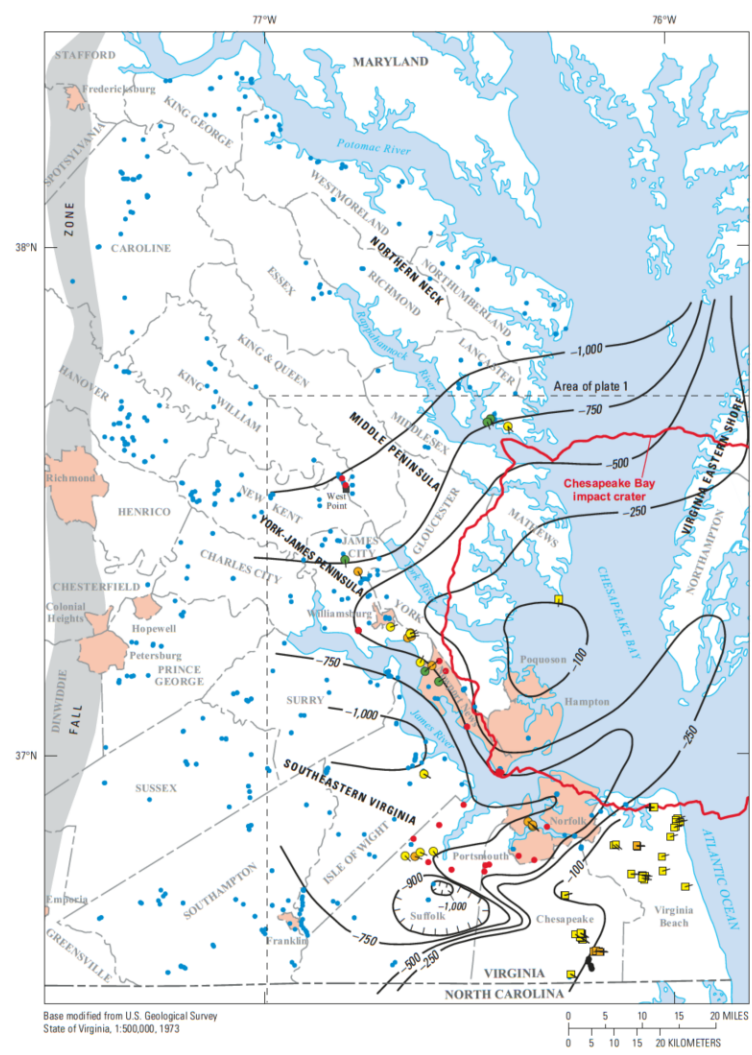
1. $(Ca^{2+}+Mg^{2+})+(HCO_3^-+CO_3^{2-})$ type water, dominated by calcium and magnesium cations, bicarbonate and carbonate anions, and commonly referred to as “hard” water,
2. $(Na^++K^+)+(HCO_3^-+CO_3^{2-})$ type water, dominated by sodium and potassium cations, bicarbonate and carbonate anions, and commonly referred to as “soft” water, and
3. $(Na^++K^+)+(Cl^-)$ type water, dominated by sodium and potassium cations, chloride anions, and commonly referred to as “salty” water.

The hydrochemical facies evolution, as discussed above for the Potomac aquifer, is also evident in the Piney Point and Aquia aquifers. These confined aquifers, which lie above the Potomac aquifer in the VCP system, exhibit less distinct transitions between hard, soft, and salty water. The muted transitions in these aquifers are primarily attributed to the composition of the sediments and residence times (depth and distance of travel) of groundwater. The sediments of the Piney Point and Aquia aquifers contain higher concentrations of calcium-magnesium carbonates compared to the deeper Potomac and are typically “harder”. The shallower depth of these aquifers results in groundwater having a shorter residence time, leading to less chemical evolution.

In the shallow aquifer system, the flow path lengths tend to be short and direct because the recharge and discharge areas are close together. As a result, the groundwater of the surficial and Yorktown-Eastover aquifers are generally characterized as less chemically evolved and spatially complex. This lack of hydrochemical evolution is also true for the sampled basement bedrock. However, it should be noted that the sampling density for basement bedrock is limited and restricted to samples collected within the western VCP as part of a USGS study of hydrogeology of the Fall Zone (McFarland, 1999).



(a) Simulated hydraulic head and groundwater total ion concentration in the Potomac aquifer in 2003. Figure from [McFarland \(2015\)](#); hydraulic head contours from [Heywood and Pope \(2009\)](#); total ion concentration from [McFarland \(2010\)](#); Chesapeake Bay impact crater from [Powers and Bruce \(1999\)](#).



(b) Approximate altitude and configuration of the 250 milligrams per liter chloride iso-concentration surface in the Potomac aquifer (McFarland, 2015).

Figure 38: Simulated Potomac aquifer groundwater levels and chloride concentrations.

3.1.2 Saltwater-Transition Zone

The location of the saltwater-transition zone is roughly coincident with the 500 mg/L total ion concentration contour as depicted in Figure 38a. This zone of salty water includes the inland saltwater wedge, and its formation is recognized to predate large groundwater withdrawals (McFarland and Bruce, 2005). While localized increases in chloride concentrations of several percentage points have been observed in response to groundwater withdrawals (Smith, 1999), regional saltwater intrusion has not been widely observed in response to the pumping-induced declines in water level that reversed the regional hydraulic gradient in the 20th century.

The saltwater-transition zone in the VCP shows a noticeable eastward rise in the total ion concentration of groundwater along the outer edge of the Chesapeake Bay impact crater. This transition coincides with a change in the major ion type of the groundwater, evolving from a “soft” water composition characterized by the presence of sodium, potassium, bicarbonate, and carbonate ions to a “salty” water composition dominated by sodium, potassium, and chloride ions. This shift in major ion type is attributed to the mixing of groundwater with seawater that permeates the sediments beneath the Atlantic Ocean and along the crater boundary, leading to the superseding of bicarbonate as the dominant anion.

Being the most conservative (nonreactive) of the dissolved ions, chloride is commonly used as an indicator of groundwater salinity and saltwater intrusion. The current EPA guideline for the upper limit of chloride in drinking water is set at 250 mg/L. The 250 mg/L iso-concentration contour also defines the leading edge of the saltwater-transition zone. Figure 38b illustrates the depth at which this 250 mg/L chloride concentrations are anticipated throughout the most of the VCP. As discussed in Section 1.4.2, above, the saltwater-transition zone marks the distal edge of the freshwater flushing and defines the pre-stress conditions of groundwater chloride.

3.1.3 Trends

The rate of chloride concentration change was assessed for numerous Potomac aquifer records (McFarland, 2010). Plotting these rates of change identified two broadly fan-shaped areas flanking the outer rim of the impact crater (Figure 39). The first extends across the York-James Peninsula and Middle Peninsula, extending east and south. The second extends across much of the area south of the James River, including Southampton County and extending east and northeast across cities of Suffolk, Chesapeake, Portsmouth, and Norfolk.

3.1.4 Eastern Shore Groundwater Quality

The vast majority of Eastern Shore groundwater wells have been infrequently sampled, with nearly half only sampled once (McFarland and Beach, 2019). Consequently, changes in chloride concentration over time can be observed in few wells. An examination of compiled data, indicates that wells with sufficient collection periods and sample quantities showed fluctuating concentrations that ebb and flow over time. These fluctuations probably reflect localized saltwater upconing and downconing caused by variations in nearby pumping.

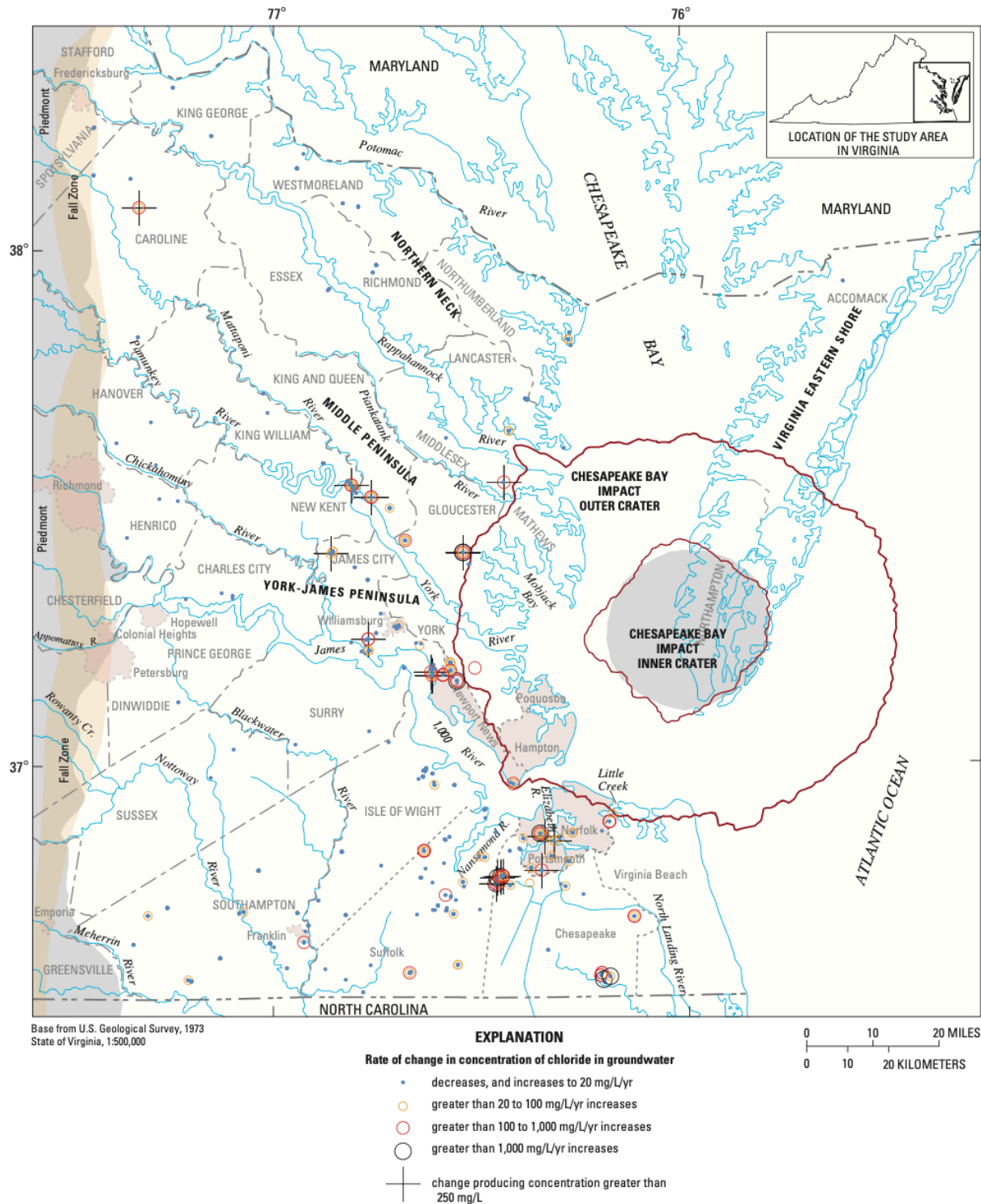


Figure 39: Concentration changes in groundwater chloride in the Potomac aquifer of the Virginia Coastal Plain (VCP). Rates calculated from 807 changes in chloride concentration over periods of 90 days or more in 229 wells from 1948–2006. [mg/L, mg/L/yr]. Reproduced from [McFarland \(2010\)](#).

On the Eastern Shore, chloride concentrations increase with depth. Along the spine of the Eastern Shore, the depth of the saltwater-transition zone is approximately 300 feet below mean sea level (BMSL). Along the southern portion of the Eastern Shore and along the coasts, the saltwater-transition zone abruptly elevates to approximately 150 feet BMSL or shallower near the coasts. As illustrated in Figure 18, these abrupt saltwater-transition zone elevations are most prominent along the coasts especially in northeast Accomack near Chincoteague and in southwest Northampton near Cape Charles. The deepest portions of the 250 mg/L chloride surface roughly coincide with the base of the lower Yorktown-Eastover aquifer and the top of the St. Marys **confining unit**.

As on the mainland, groundwater ages on the Eastern Shore indicate that the configuration and position of the saltwater-transition zone largely reflects pre-stress conditions (McFarland and Beach, 2019). This is because groundwater movement is too slow to have traversed significant distances. Instead, deep portions of the saltwater-transition zone experience downward **leakage** of fresh groundwater in the Yorktown-Eastover aquifer system. Shallower portions of the saltwater-transition along the coast reflect upward leakage and discharge into the Chesapeake Bay and Atlantic Ocean. Current withdrawals, however, have resulted in water levels falling below sea level, which creates the conditions for lateral saltwater intrusion. The increasing chloride trends along the Eastern Shore margins have been well documented (Richardson, 1993; Nowroozi et al., 1999; McFarland and Beach, 2019), and have been predicted to occur and to continue under current permitted withdrawal scenarios (Sanford et al., 2009a; DEQ, 2024a)

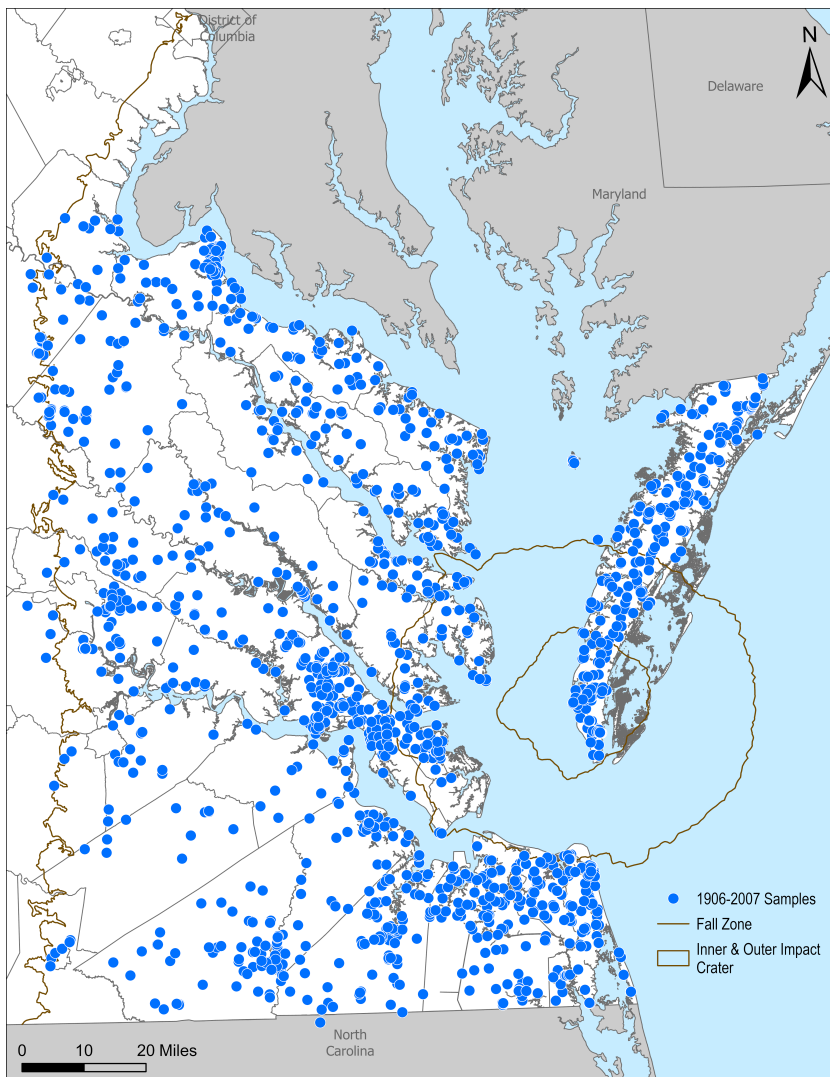
3.2 Groundwater Quality Data Update and Assessment

The groundwater-quality dataset presented by McFarland (2010) and covering the period of 1906–2007 has been updated to include data from the period of 2007–2024. This update was principally completed following procedures outlined in McFarland (2010). Rather than searching individual data repositories, however, the current update was completed through the Water Quality Portal (WQP) hosted by EPA (National Water Quality Monitoring Council et al., 2021). This portal pulls data from the USGS NWIS and the EPA Water Quality Exchange Data Warehouse, which includes the legacy Storage and Retrieval database (STORET).

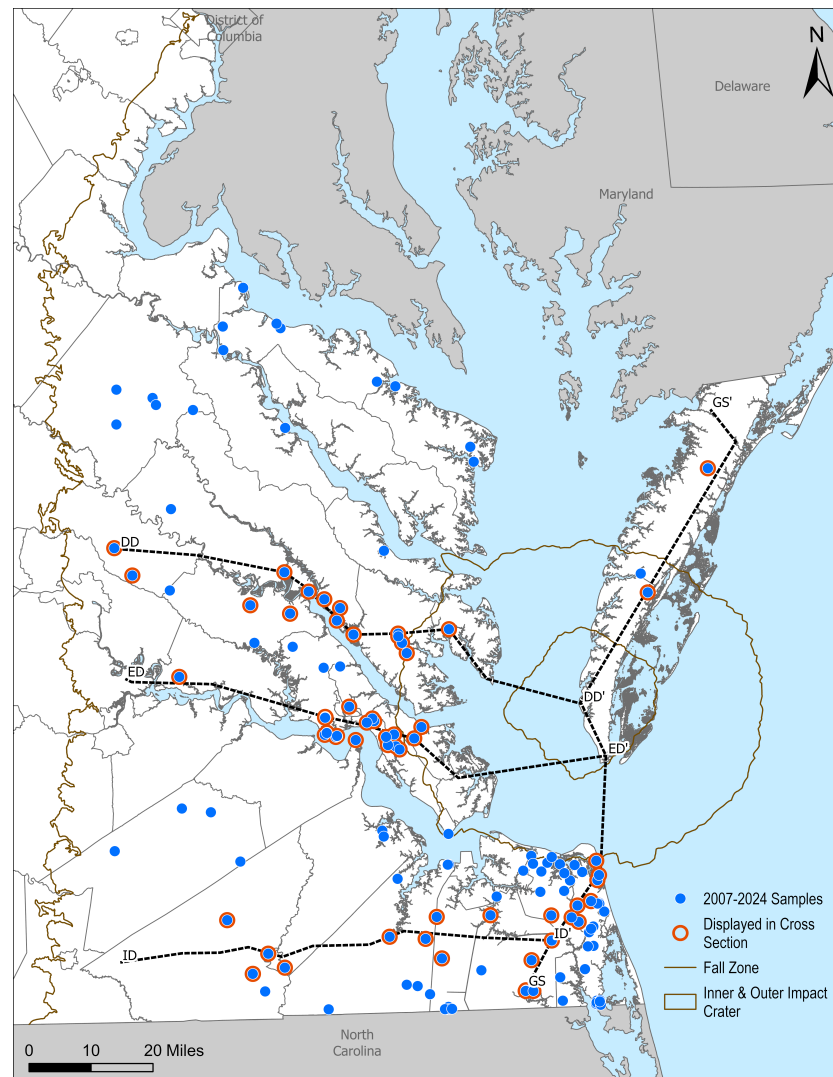
The data update encompassed a study area consisting of the full VCP and coincident with the area defined by McFarland (2010). The spatial extent of this study area was specifically defined as the area between Latitude 36°30' and 38°30' N, and Longitude 75°30' and 77°30' W, covering an area of approximately 13,000 square miles. As necessary, individual samples were investigated to fill in metadata gaps related to location and well construction.

To ensure data quality is adherent to standard USGS sampling standards, the data included in this compilation are limited to those obtained from the WQP and from McFarland (2010). Additional data are available from certain locations where regulated entities monitor local groundwater quality as a condition of their groundwater withdrawal permits. Due to the uncertainty in sampling procedures used by permitted facilities, these data are not included in this compilation. In limited cases, however, these permit-related data have been used to assess trends in groundwater quality (see Section 3.5.2, Case Study: West Point Mill Withdrawal).

Figure 40 illustrates the spatial distribution of the compiled data and serves as a reference for defining the study area. The addition of data collected between 2007 and 2024 does not substantially increase the sampling density or expand the study area extent. This amendment resulted in an 8% increase in total reported results, from 10,166 to 10,986. The additional 820 individual samples are attributed to 313 unique sites. This resulted in an increase of unique sites in the full dataset from 1,991 to 2,194, or an increase of more than 10%. The majority of 2007–2024 data is associated with the deep Potomac aquifer and the unconfined surficial aquifer. A detailed summary of the data amendment is provided in Table 11.



(a) Sample locations compiled for the period 1906–2007. Adapted from (McFarland, 2010).



(b) Sample locations compiled for the period 2007–2024, this study. Select transects from the report are also shown: DD–DD', ED–ED', ID–ID', and GS–GS'. Adapted from McFarland (2010).

Figure 40: Groundwater-quality sample locations and cross-section transects.

Further, newly added data were assessed for acceptability following the procedures outlined in [McFarland \(2010\)](#). These acceptance criteria included charge-balance screening and chloride-concentration screening through correlation with specific conductance measurements to measure concentration accuracy; see [McFarland \(2010\)](#) for additional details. As summarized in Table 11, major ions associated with 2,379 samples (23.4 percent) were deemed acceptable. An additional 1,722 chloride concentrations were deemed acceptably accurate. In total, 4,662 individual chloride concentrations were deemed complete, accurate, and acceptable.

Major ions passing the acceptance criteria were used to categorize samples as either hard, soft, or salty. Comparing panels in Figure 41 illustrates that the general distribution of water type within the Potomac aquifer from 1906–2007 has remained consistent through the period of 2007–2024 and conforms well with the eastward water-type evolution ([McFarland, 2010](#)). The water-type transition interfaces in the deep aquifer system continue to appear stable since the early 19th century. The overall stability of these transition interfaces, especially that of the soft-to-salty transition, supports the notion that current groundwater chemistry continues to reflect pre-stress conditions. Strong similarities between 1906–2007 and 2007–2024 water-type data are expected, given that the processes controlling hydrochemical facies evolution operate on geologic timescales. In contrast, the chemical composition of the shallower aquifers and basement bedrock along the Fall Zone is more variable due to short flow paths between recharge and discharge areas and from anthropogenic impacts.

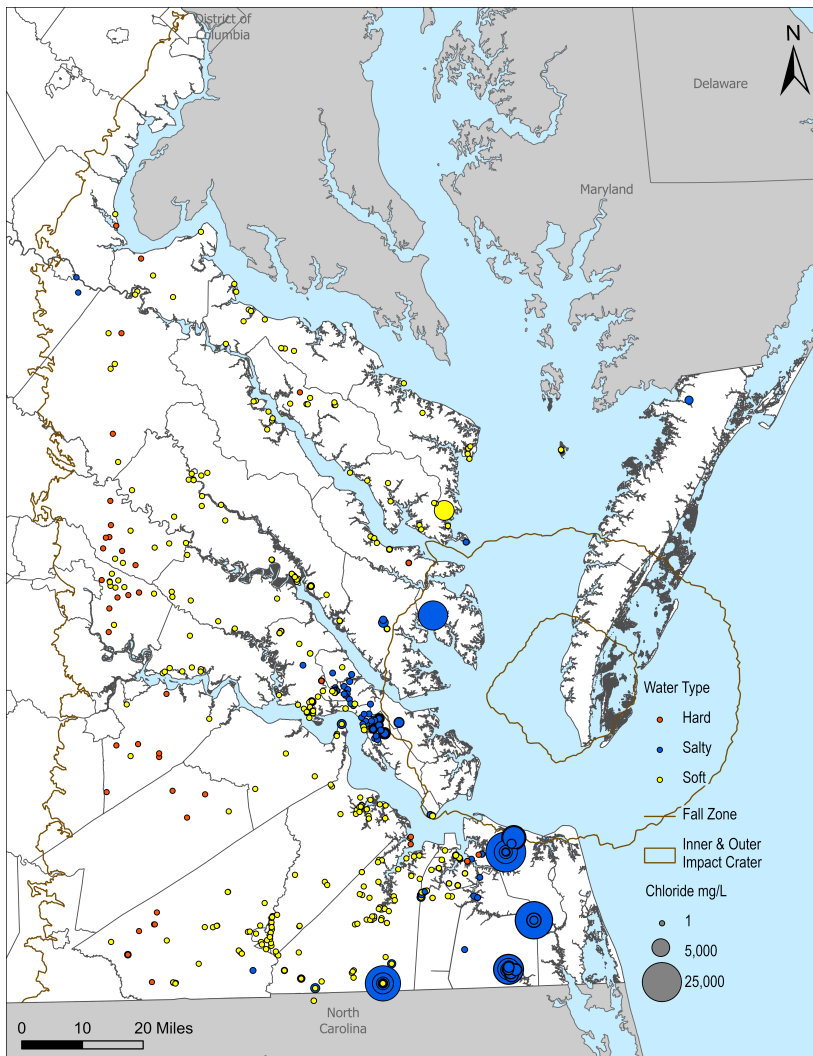
Figure 41 presents proportionally scaled groundwater chloride concentrations in the Potomac aquifer and illustrates that chloride increases eastward (and with depth). This eastward increase forms salty-type groundwater that delineates the saltwater-transition zone, which represents the interface between freshwater from the west and saline waters from the east (Figure 41). The regional saltwater-transition zone is a stable interface where movement occurs over geologic time scales. As noted by [McFarland \(2010\)](#), despite more than a century of data and continuous groundwater withdrawals, the overall position of the saltwater-transition zone has not substantially changed. On shorter time scales, groundwater withdrawals can result in localized intrusion, mostly along shallow parts of the zone. Short-term withdrawal cycling can cause repeated upconing and downconing cycles of chloride concentrations from deeper more saline waters. Over the long term, these cycles can induce lateral intrusion ([McFarland, 2010](#)). Areas proximal to the saltwater-transition zone, such as along the boundary of the impact crater, are more susceptible to local-scale lateral migration and upconing.

Few groundwater samples were collected from the Eastern Shore in the period 2007–2024. Therefore, interpretation of groundwater quality is limited to modeling simulations completed by [McFarland and Beach \(2019\)](#), as well as the new groundwater budget analyses presented in Section 2.4. On the Eastern Shore, the available sample data have not shown widespread regionally increasing salinity. The current configuration of saltwater-transition zone on the Eastern Shore largely reflects the pre-stress (pre-pumping) groundwater flow patterns. There is evidence, however, of localized intrusion likely stemming from anthropogenic withdrawals. These withdrawals have lowered water levels and increased the potential for saltwater intrusion, as shown in modeling outputs (Figure 18). Freshwater is still infiltrating and moving through the system, leaking downward in areas of the saltwater-transition zone and upwards in shallower areas and discharging at the coast. An anomalous ridge of salty water cuts across the peninsula. This feature is linked to the Exmore **paleochannel**, which has acted to drain and lower groundwater levels that then draws the saltwater-transition upwards. Chloride increases with depth, such that depths of about 300 feet BMSL are typically associated with chloride concentrations of 250 mg/L or higher ([McFarland and Beach, 2019](#)). A new, limited program of Eastern Shore sampling has been initiated by DEQ. Results from this sampling program are expected to provide an update to baseline groundwater chemistry on the Eastern Shore.

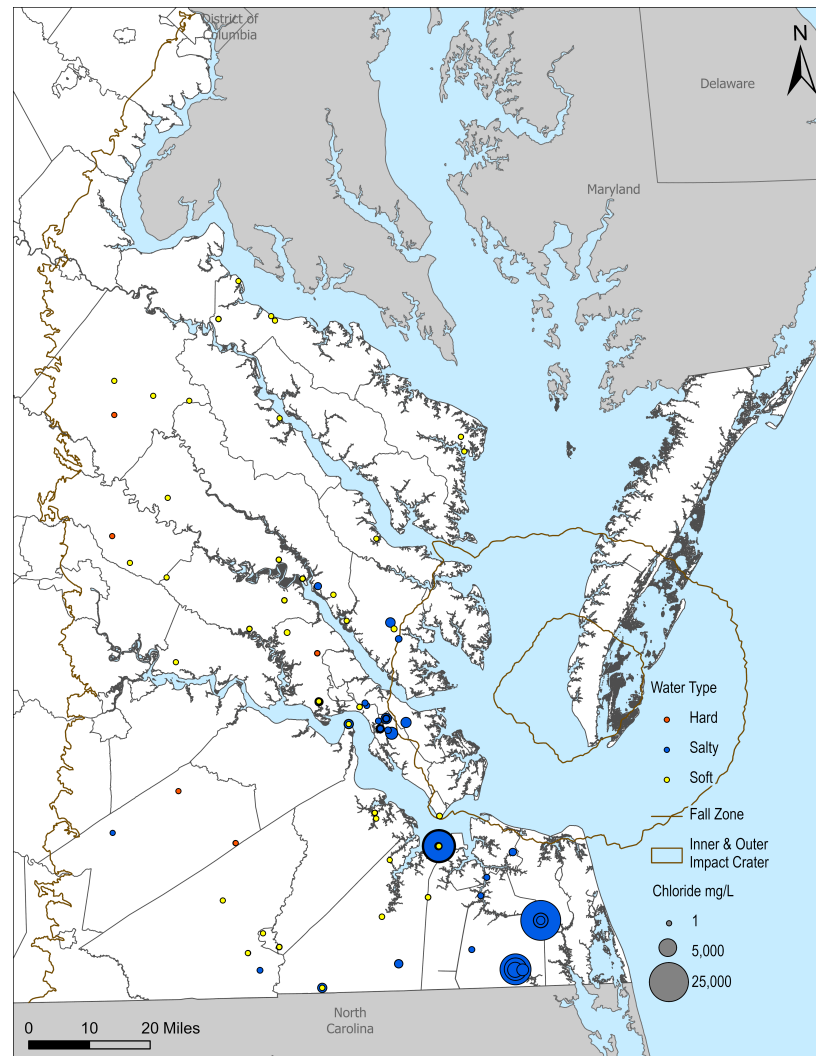
Similar assessments could be completed for other groundwater constituents such as fluoride, iron, manganese, nitrates, and others. Overall, recent data have not changed the basic descriptions of groundwater quality and trends related to major ions and chloride outlined in previous studies ([McFarland, 2010](#); [McFarland and Beach, 2019](#)). The subsequent sections will provide context and evidence in support of this assertion through updated **cross-sections** depicting chloride concentrations at depth, Piper diagrams, and trend analyses.

Table 11: Water Quality Data Summary

Data Type	1906–2007		2007–2024 Update		Combined N	% Increase
	N	% of Total	N	% of Total		
Years Covered	101	–	17	–	118	16.8
Total Samples	10,166	–	820	–	10,986	8.1
Unique Sites	1,991	–	313	–	2,194	10.2
Sample Frequency by Stratigraphic Zone						
Basement	826	8.1	–	0	826	0
Potomac Aquifer	3,334	32.8	335	40.9	3,669	10
Potomac Confining Zone	78	0.8	–	0	78	0
Upper Cenomanian Confining Unit	25	0.2	3	0.4	28	12
Virginia Beach Aquifer	13	0.1	4	0.5	17	30.8
Virginia Beach Confining Zone	–	0	–	0	–	–
Peedee Aquifer	13	0.1	2	0.2	15	15.4
Peedee Confining Zone	7	0.1	–	0	7	0
Aquia Aquifer	62	0.6	21	2.6	83	33.9
Nanjemoy-Marlboro Confining Unit	183	1.8	2	0.2	185	1.1
Exmore Clast Confining Unit	47	0.5	–	0	47	0
Exmore Matrix Confining Unit	22	0.2	–	0	22	0
Chickahominy Confining Unit	26	0.3	2	0.2	28	7.7
Piney Point Aquifer	422	4.2	37	4.5	459	8.8
Calvert Confining Unit	26	0.3	4	0.5	30	15.4
St. Mary's Aquifer	14	0.1	–	0	14	0
St. Mary's Confining Unit	177	1.7	8	1	185	4.5
Yorktown-Eastover Aquifer	2,362	23.2	87	10.6	2,449	3.7
Yorktown Confining Zone	298	2.9	44	5.4	342	14.8
Surficial Aquifer	2,231	21.9	271	33	2,502	12.1
Subtotal	10,166	100	820	100	10,986	8.1
Acceptable Major Ion Concentrations Based on Charge Balance	2,379	23.4	557	67.9	2,936	23.4
Acceptable Chloride Results based on Conductance Relationship	1,623	–	103	–	1,726	–
Total Acceptable Chloride Concentrations	4,002	39.4	660	80.5	4,662	16.5



(a) Potomac aquifer groundwater quality samples 1906–2007 (McFarland, 2010).



(b) Potomac aquifer groundwater quality samples 2007–2024.

Figure 41: Distribution of groundwater type in the Potomac aquifer of the VCP for the periods listed. Orange indicates “hard” type water, yellow indicates “soft” type water, and blue indicates “salty” type water. Symbol size is scaled proportionally to the median chloride concentration of the respective record. The concentration of salty-type waters is coincident with the saltwater-transition zone.

3.3 Cross-Sectional Analysis

3.3.1 Methods

In a broad assessment of groundwater in the VCP, [McFarland \(2010\)](#) plotted chloride concentrations at depth along transects used in the earlier framework of the Coastal Plain ([McFarland and Bruce, 2006](#)). A selection of transects presented in [McFarland \(2010\)](#) are shown in this report with updated groundwater quality samples from 2007–2024 overlain on cross-sections highlighted in Figure 40b.

Selection of these transects was informed by data availability and sub-regional representation. As shown in Figure 40b, DD to DD' generally follows the Middle Peninsula beginning north of the City of Richmond and crosses the Chesapeake Bay and terminates in Cape Charles. ED to ED' generally follows the York-James Peninsula starting south of the City of Richmond and crosses the Chesapeake Bay to the southern tip of the Eastern Shore. ID to ID' crosses the region south of the James River, beginning in western Sussex County and ending in eastern City of Chesapeake. GS to GS' begins in the southern area of the City of Chesapeake, continues north across the Chesapeake Bay and transects the Eastern Shore and terminates at the Virginia–Maryland state line.

Data from the period of 2007–2024 were used to update cross-sections illustrating 1906–2007 chloride concentration contours published in [McFarland \(2010\)](#). Accepted groundwater-quality data from 2007–2024 that fell within a predetermined distance of each transect were selected for use in updating the cross-sections. These cross-sections depict chloride concentration iso-contours published by [McFarland \(2010\)](#) (plates 10, 12, and 14). For the three east–west trending transects DD–DD', ED–ED', and ID–ID', data from wells within a five-mile buffer were selected. A two-mile buffer was used for data selection along the north–south trending transect (GS–GS'). Sample locations overlain in cross-section are highlighted in orange in Figure 40b.

New sample locations overlain on [McFarland's](#) original cross-sections were scaled to match the vertical and horizontal projection of the original samples, such that a new sample taken at the same well would display over the previous sample. Due to the lack of well construction information associated with some of the updated dataset, a subset of samples are attributed to the altitude of the bottom of reported well depth. This differs from the approach of [McFarland \(2010\)](#) who, by way of a more complete dataset, attributed all chloride concentrations to the top-of-screen altitude. The result of this difference is the potential for chloride concentrations to be projected deeper in the cross-sections relative to corresponding data from 1906–2007 period. An assessment of the projected data did not identify any major inconsistencies, but care should be taken when interpreting these results.

3.3.2 Results and Discussion

Several VCP cross-sections created using 1906–2007 chloride concentration data and on which iso-concentration contours were drawn have been updated to include data from the 2007–2024 period. In comparison, data from 2007–2024 conforms well with 1906–2007 data. These updated cross-sections may be useful in making subtle refinements to the position of both iso-concentration contours and differential flow pathways. Differential flow pathways represent interconnections within the complex geologic strata whereby higher **hydraulic conductivities** allow for preferential flow of freshwater. These preferential flow paths often result in inverted chloride concentrations, where denser saltier waters overlay fresher less-dense water moving preferentially at depth. An example of a prominent chloride inversion is illustrated along the western edge of ID–ID' (Figure 45).

Stratigraphic and geographic changes may be encountered over short distances. When using a selection radius along a transect from which to include water quality samples, differences in stratigraphy are expected. An example of this stratigraphic discrepancy is evident in the ED–ED' transect in Figure 44, where high chloride concentrations are projected in the Yorktown-Eastover aquifer. The chloride concentration of 1,380 mg/L and 2,560 mg/L were collected from 56F 65 and 57F 37. Construction information for these wells indicate they are **screened** in the surficial aquifer on Jamestown Island. The high chloride concentrations are likely reflective of a connection with the brackish and tidally-influenced James River.

Based on the updated cross-sections, only minor potential changes in the groundwater iso-concentration contours are noted. Two such changes are noteworthy. In transect DD-DD' (Figure 43, one chloride concentration of 49 mg/L in western King and Queen County is shown corresponding with the fork of the differential flushing flow path. The position of this data point is deeper than the 50 mg/L iso-concentration contour. This both supports the position of the preferential flow path within the frame of the DD-DD' cross-section and indicates that the 50 mg/L and the lower 250 mg/L contours could be refined to a deeper position. Similarly, in ID-ID' (Figure 45 a chloride concentration of 184 mg/L (58B284 SOW 253A) in the City of Suffolk is identified at the deeper end of the predicted (dashed) path of differential flushing. As the newest VCP SOW in the network, the well construction and depth of 58B284 SOW 253A is complete and accurate. The implication of the data associated with 58B284 SOW 253A is that the estimated position of the differential flushing line can be accepted and the estimated (dashed) iso-concentration contour(s) can be refined. Along the eastern portion of ID-ID', near the Nottoway River and the City of Franklin, there is notable freshwater deep in the Potomac aquifer. This freshwater signal could be related to local **faulting**, but ultimately the reason is unknown and requires further investigation. Regardless, the iso-concentration contours in this region could be refined to reflect this freshwater signal.

Figure 46 illustrates that data from the period 2007–2024 conforms well with the iso-concentration contours created using 1906–2007 period data. Trapped saline groundwater within the crater is evident but unconfirmed by current data. The elevated chloride concentrations and inversions associated with eastern edge of the crater are notable and supported by the 2007–2024 data. The paucity of data for the Eastern Shore precludes additional interpretation. As mentioned previously, a DEQ-led Eastern Shore groundwater-quality sampling program is currently underway. Once completed, results from this sampling program will help confirm or refine the iso-concentration contours for the Eastern Shore. In summary, the interpretations of regional groundwater chloride distribution made by McFarland (2010) continue to be accurate and reflective of current groundwater chloride conditions.

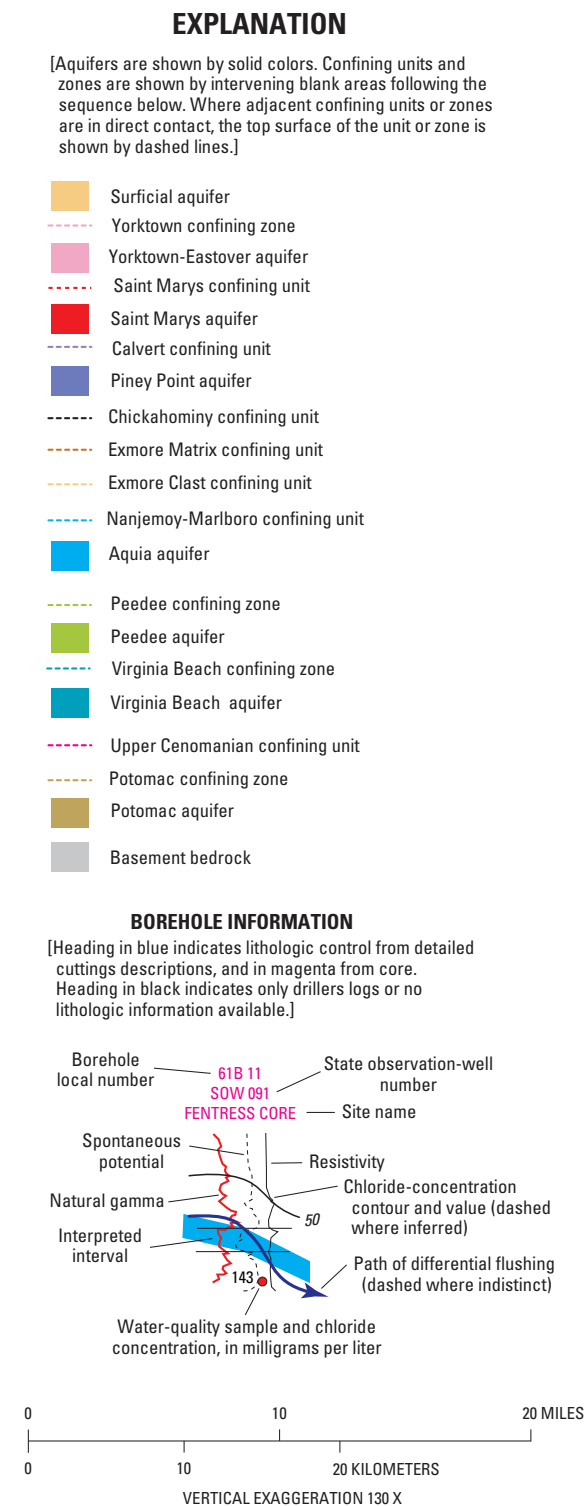


Figure 42: Legend from McFarland (2010) for use with subsequent Figures 43, 44, 45, and 46.

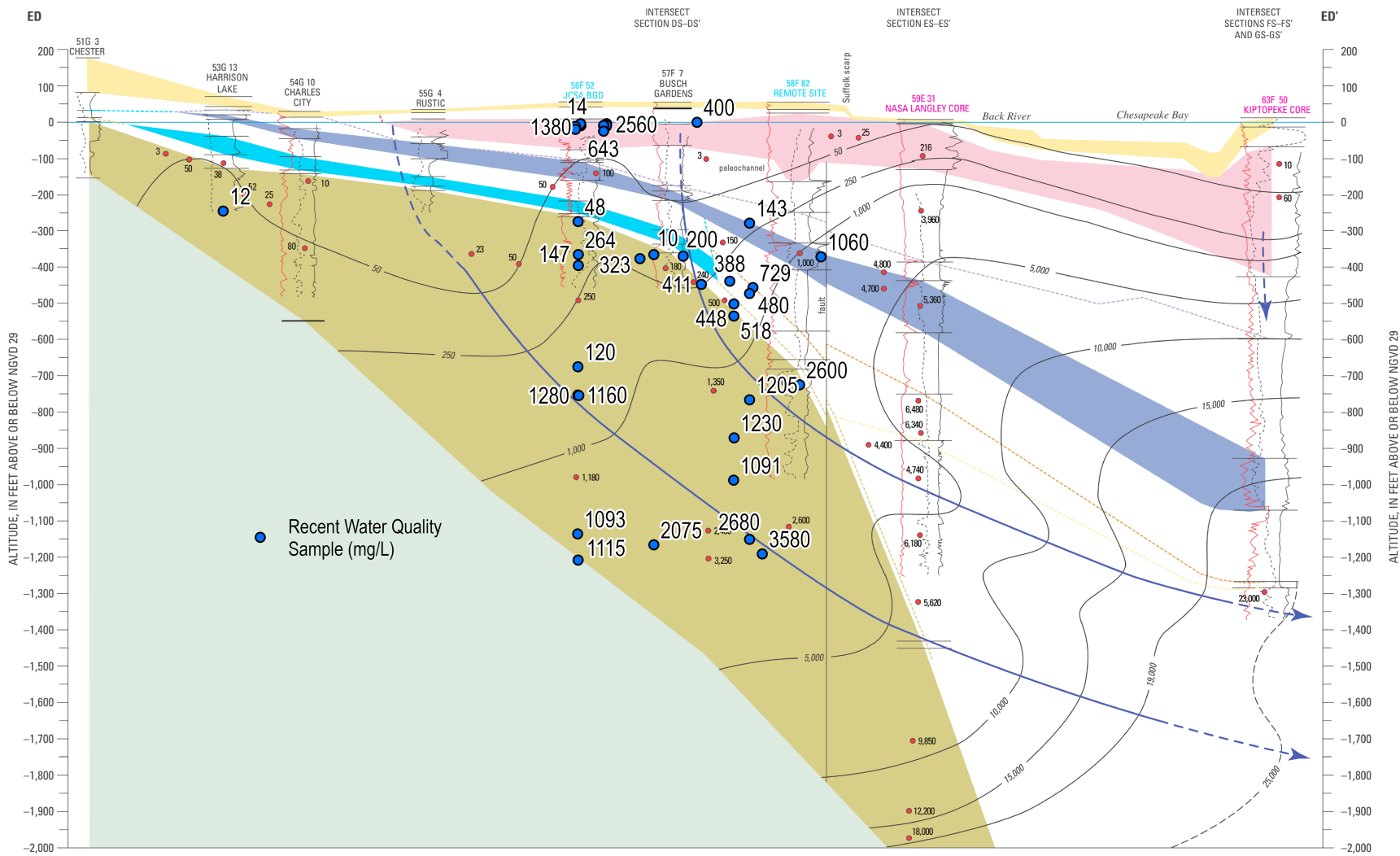


Figure 44: ED to ED' cross-section from [McFarland \(2010\)](#) and shown in Figure 40b, superimposed with select water-quality sample chloride concentrations from 2007–2024 (blue circles).

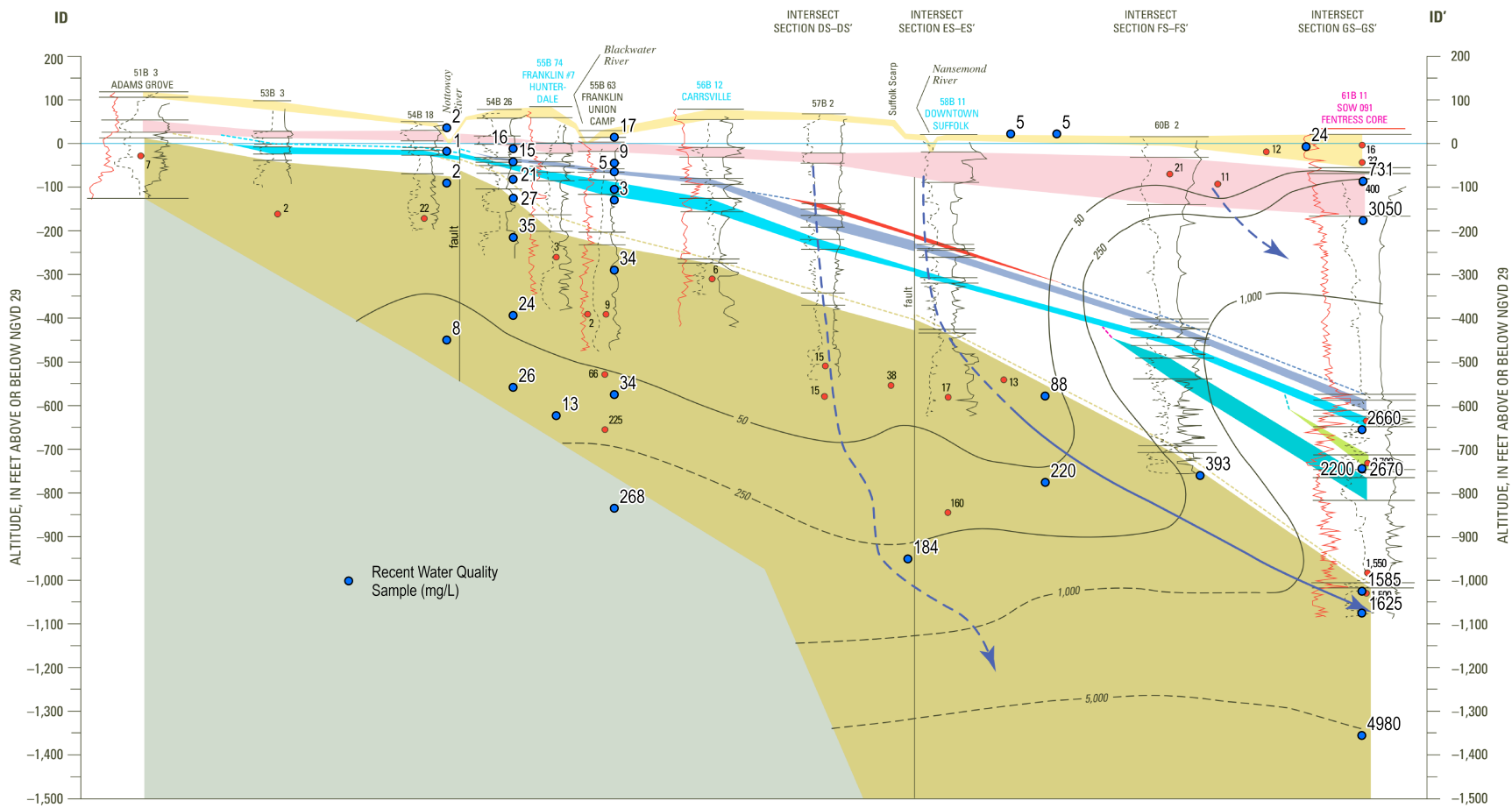


Figure 45: ID to ID' cross-section from [McFarland \(2010\)](#) and shown in Figure 40b, superimposed with select water-quality sample chloride concentrations from 2007–2024 (blue circles).

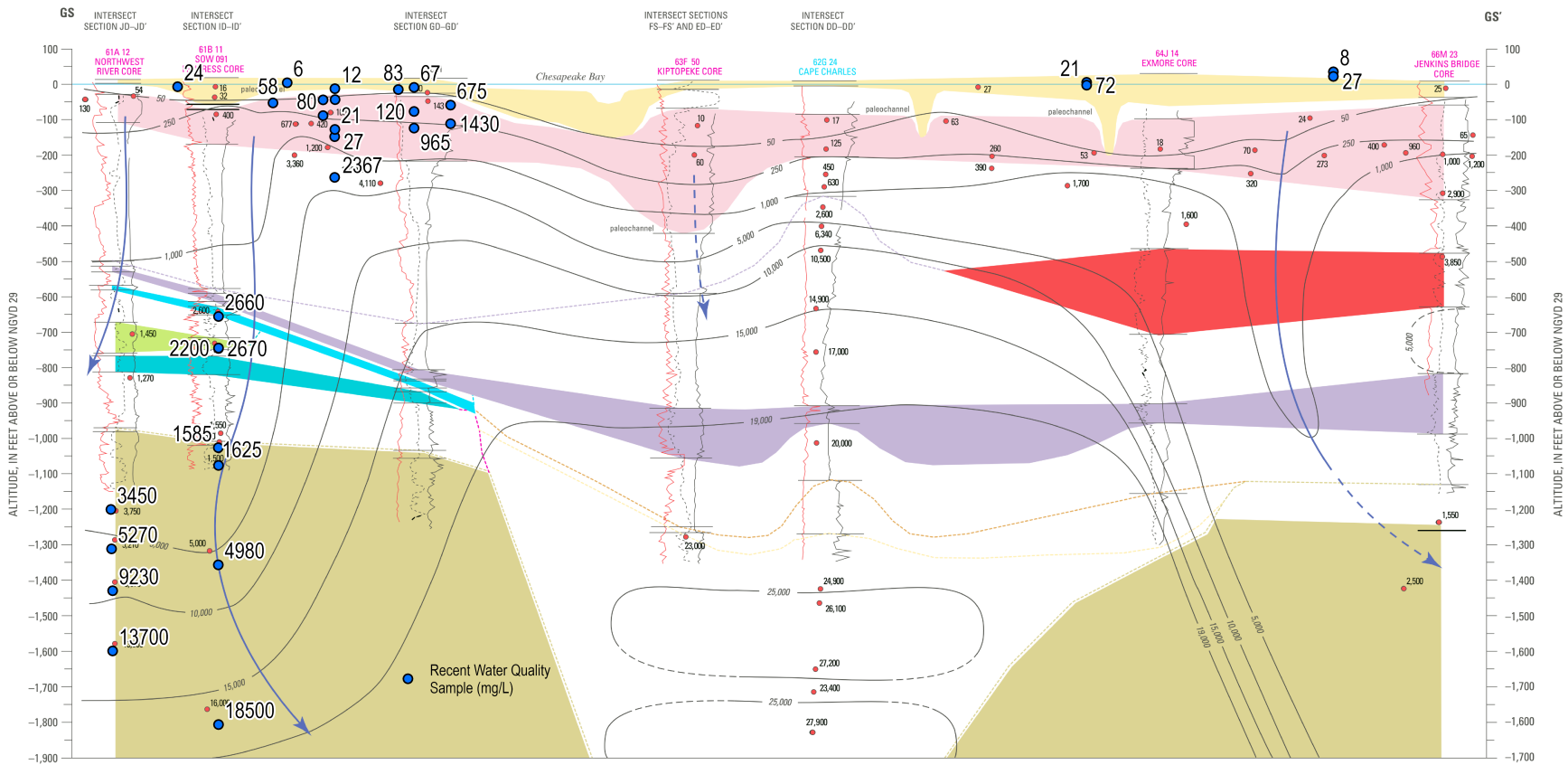


Figure 46: GS to GS' cross-section from [McFarland \(2010\)](#) and shown in Figure 40b, superimposed with select water-quality sample chloride concentrations from 2007–2024 (blue circles).

3.4 Hydrochemical Facies Analysis

Hydrochemical **facies** are defined as three-dimensional zones of groundwater with broadly similar chemical characteristics. A sequence of facies represents the evolution of groundwater as it gradually flows through the VCP aquifer system. The composition and position of these facies were assessed using Piper trilinear diagrams to determine if any substantial changes have occurred since the earliest data was collected.

3.4.1 Methods

Piper trilinear diagrams were constructed using graphing software to analyze variations in hydrochemical facies composition between the periods of 1906–2007 and 2007–2014 (Golden Software, 2023). The Piper diagram consists of two ternary plots: one representing the major cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) and another representing the major anions (Cl^- , SO_4^{2-} , HCO_3^- , CO_3^{2-}). Ionic composition from these plots are projected into a central diamond-shaped plot, which combines the anion and cation compositions and classifies each water samples into four different hydrochemical facies, as shown in Figure 47.

The entire water-quality dataset was compiled from multiple databases, as described earlier in Section 3. For the period 1906–2007 (excluding 2007 samples), data were collected from McFarland (2010) USGS groundwater-quality investigation report, and for the period of 2007–2024 (including 2007 samples) water-quality data were collected from the WQP.

Water samples were organized according to GBRs to characterize regional variations. Additionally, to discuss spatial variability in groundwater hydrochemical facies, the samples were grouped into 3 categories based on their proximity to the Chesapeake Bay and Atlantic Ocean: western, eastern, and central. These grouping generally coincide with the GBRs as follows: the western group (western GBRs) including the Northwest Coastal Plain, Middle James regions, and parts of Chowan region; the eastern group (eastern GBRs) including the Northern Neck region, and parts of Middle Peninsula, York-James, and Southeast Virginia regions; and the central group (central GBRs) including parts of the Middle Peninsula, York-James, and Chowan regions.

Laboratory analysis reports the major anion and cation concentrations in mg/L. As groundwater chemistry data was compiled from multiple federal and state agency databases (McFarland, 2010); the specific laboratory techniques used for ion analysis are not documented and may have varied over the long study period (1906–2024). Samples with a charge balance error greater than 10% and incomplete ion data were excluded from the study. Ion concentrations were converted from milligrams per liter to milliequivalents per liter (meq/L) by dividing the ion concentration by atomic weight and multiplying by valence number. Finally, ion concentrations in meq/L were converted to % meq/L (known as relative concentrations) by dividing each anion by the total anion and each cation with the total cation concentrations.

3.4.2 Results and Discussion

A total of 1,885 groundwater samples for the period 1906–2024 were analyzed using Piper trilinear diagrams to assess variability in ion concentrations and identify diverse hydrochemical facies (water types) across different hydrogeologic units as shown in Figure 47. Distinct spatial variation with local trends were observed across GBRs, reflecting the influence of different aquifer and bedrock compositions. These observed trends are consistent with previous USGS investigations (McFarland, 2010).

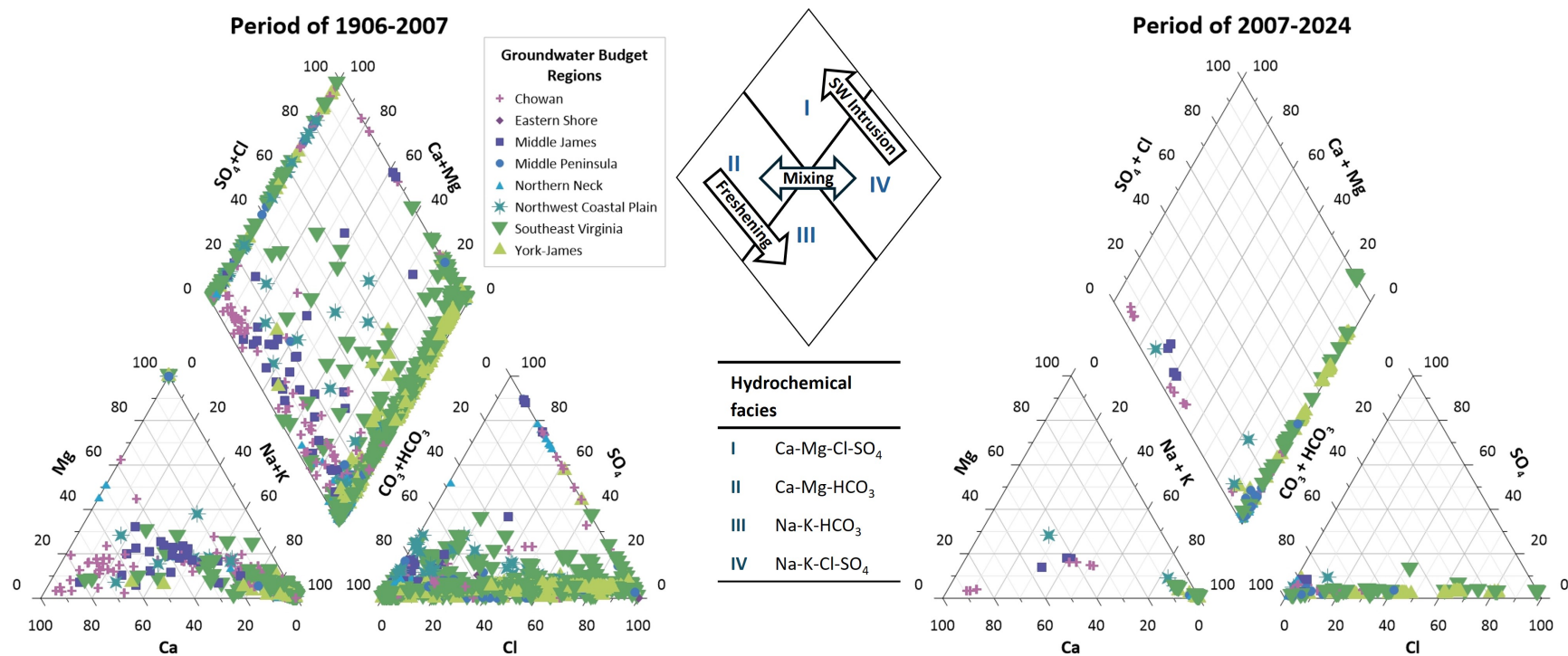


Figure 47: Piper diagrams illustrating the groundwater hydrochemical facies of the Potomac aquifer based on major ionic composition (expressed as % meq/L). The left diagram shows samples from 1906 to 2007 and the right diagram shows samples from 2007 to 2024. Interpretative guide represented by the center figure.

Spatial and Temporal Trends in Hydrochemical Facies

Among the different VCP hydrogeologic units (Figure 5), Potomac-aquifer samples clearly exhibit sequential trends from west to east. A strong spatial dominance of hard water ($Ca^{2+}+Mg^{2+})+(HCO_3^-+CO_3^{2-})$ was found generally in the western GBR regions falling into quadrant II for both time periods. Toward the central and eastern GBR, the hydrochemical facies shift toward soft ($Na^++K^+)+(HCO_3^-+CO_3^{2-})$ water to salty water ($Na^++K^+)+(Cl^-)$, corresponding to quadrants III and IV. A few samples from the Southeast Virginia and York-James regions exhibit marked variability in the 1906–2007 dataset, this is possibly due to variability in sample collection and analysis method over the extended sample collection period.

The observed spatial pattern indicates significant mixing between freshwater and deeper saline water, more evident across the central and eastern groundwater budget regions. This phenomenon is supported by the predominance of sodium (Na^{2+}) + Calcium (Ca^{2+}) bicarbonate waters with increasing chloride (Ca^{2+}) moving eastward. No signature of saltwater intrusion was found. These findings indicate that freshwater covers the majority of the groundwater reserve; however, freshwater–saltwater mixing is happening probably due to the regional groundwater flow system (freshly recharged groundwater moving from west to east, shown as preferential freshwater flowpaths in Figure 44) and higher groundwater withdrawal across the eastern zones.

Major Ion Distribution

The total ion concentrations consistently increase eastward, with the easternmost GBRs (Southeast Virginia, York-James) having elevated total ion levels in the 1906–2007 period. Consistent patterns were recognized in the 1906–2007 data (Figure 41). The data from 2007–2024 supports these patterns but the limited quantity precludes additional interpretation.

Sodium and bicarbonate were the dominant cation and anion, respectively, during both time periods (1906–2007 and 2007–2024), with average concentrations of 548 mg/L for Na^+ and 500 mg/L for HCO_3^- . No significant changes were identified in Na and Cl levels; however, their concentrations remained consistent throughout the studied timeframes except for a few samples near areas of intensive groundwater withdrawal. When projected onto the central diamond-shaped plot, the majority (approximately 75% of 1906–2007 and 91% of 2007–2024 samples) the groundwater samples cluster within the sodium-calcium bicarbonate ($NaCaHCO_3$) and sodium bicarbonate ($NaHCO_3$) hydrochemical facies, indicating freshwater mixing with deeper saline water.

Among the cations, sodium (Na^+) was the most abundant cation with an average concentration of 550 mg/L, followed by calcium (Ca^{2+}), and potassium (K^+). Among the anions, HCO_3^- and CO_3^{2-} were dominant, with average concentrations of 617 mg/L and 397 mg/L, respectively, whereas Cl^- showed moderate levels (average, 490 mg/L). At regional scale, no significant variation was detected between the 1906–2007 and 2007–2024 time periods, indicating mostly consistent groundwater quality in the VCP.

3.5 Chloride Trend Analysis

Understanding changes and movement in groundwater chloride concentrations is essential to groundwater-resource management. Heath (1983) defined “saltwater encroachment” as the movement of the saltwater-transition zone toward fresh groundwater. With declining water levels in the VCP and the subsequent shift in hydraulic gradient, the seaward to landward movement of the saltwater-transition zone is possible and has broad implications. Additional horizontal movement of saltwater through withdrawal-induced “lateral encroachment,” or “intrusion,” is also possible (Heath, 1983). “Upconing,” defined as vertical movement of salty groundwater to a pumping well can also occur (Heath, 1983; McFarland, 2015). Since the displacement of even small volumes of water can result in upconing, it is generally accepted that upconing is a more common cause of rising chloride concentrations in groundwater than intrusion (Heath, 1983). Trend analyses of chloride records were completed and assessed to determine whether lateral migration or upconing has occurred, or is occurring, in the VCP.

3.5.1 Methods

Being the most conservative (nonreactive) of the dissolved ions, chloride is commonly used as an indicator of groundwater salinity and for monitoring saltwater intrusion. Of the 2,194 sample records in the compiled dataset, 103 records met the screening criteria of: containing eight or more data points after removing clear outliers, and the absence of data gaps exceeding one-third of the overall time-series length.

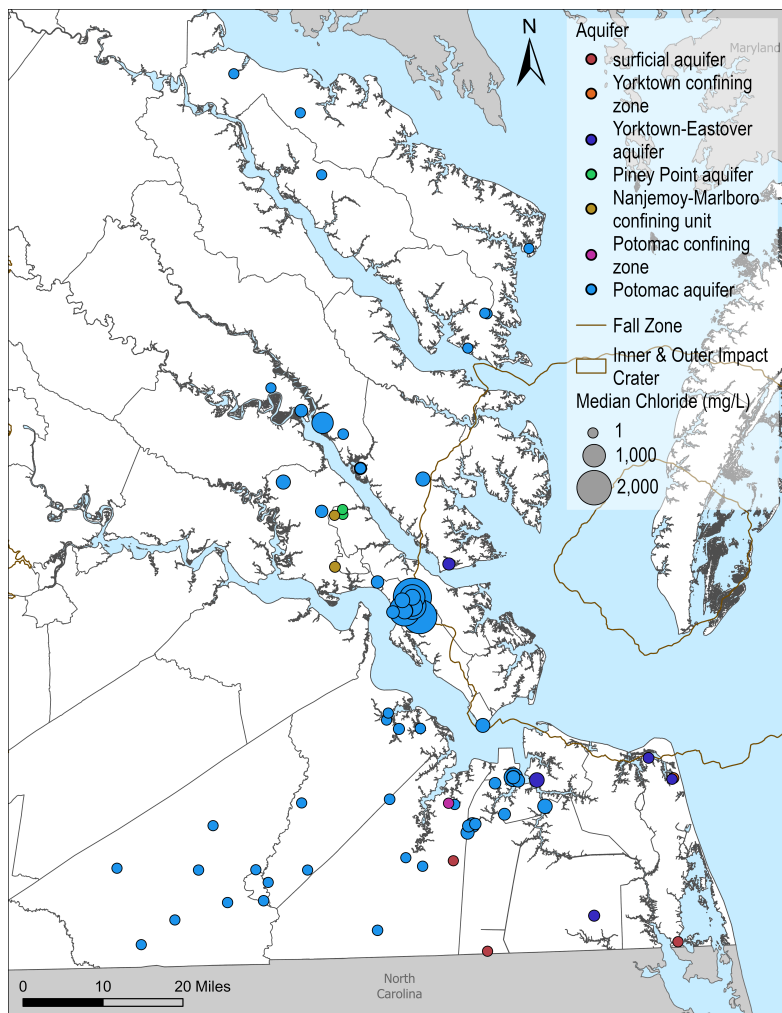
Outlier analysis involved identifying results that fell outside of 3 standard deviations (3σ) of the record mean. These ‘outliers’ were removed if justifiable. Several ‘outliers’ not meeting the 3σ criteria were removed based on judgment. For example, 56J 11 has consistent chloride concentrations in excess of 900 mg/L (median of 970.8 mg/L). Two reported concentrations of 2 and 3.1 mg/L were removed, as they appear to be false and could bias the trend analysis. Finally, sampling dates were converted to their respective quarters to allow for sampling frequency uniformity and improved data handling.

Mann-Kendall trend analysis was performed on 103 time-series of chloride concentration data using ProUCL Software (EPA, 2022), and mapped in figures 48 and 49. The Mann-Kendall (MK) test is a non-parametric time-series analysis used to identify monotonic trends and test statistical significance of identified trend. The MK test differs from parametric tests, like linear regression, in that the data is not required to be normally distributed. Further, the MK test is capable of handling time-series in which there are data gaps.

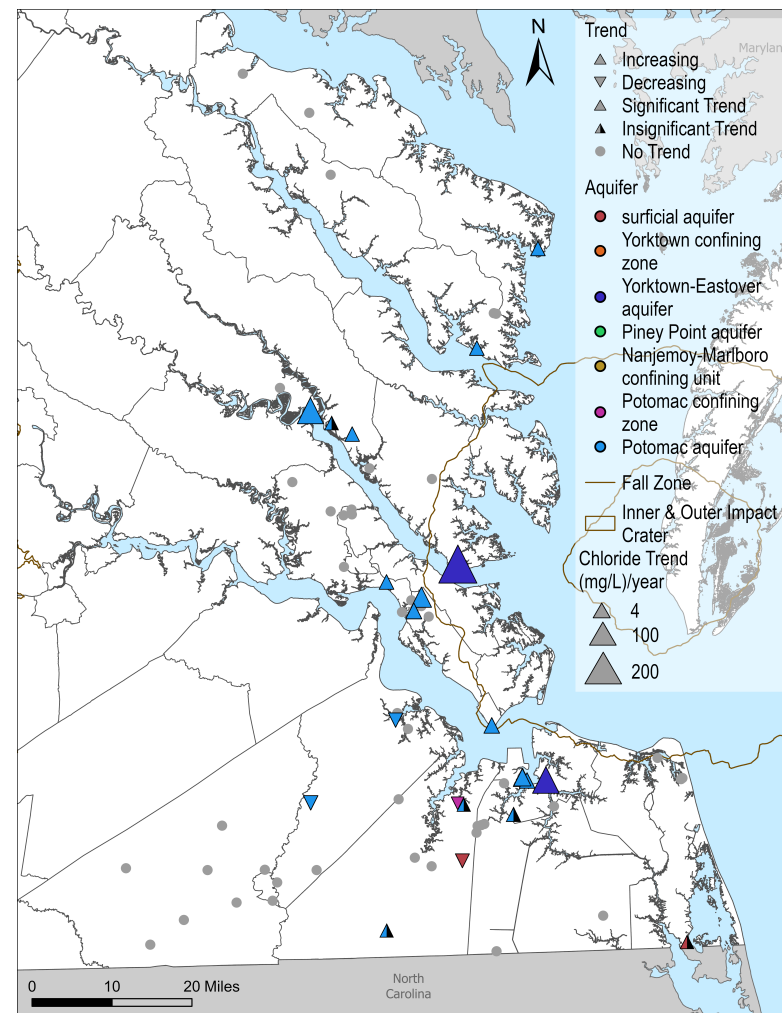
The MK test compares data points in a time series against all subsequent data points. The aggregate of these comparisons (or scores) is the S-statistic, the sign of which indicates the direction of the trend. A positive S value is suggestive of an increasing trend and conversely a negative S value is suggestive of a decreasing trend. Values close to 0 indicate no significant trend. The S-statistic is used to calculate a p-value to determine significance. A trend is deemed significant if the calculated p-values is less than 0.05 (95% confidence interval). On occasion trends were classified as “increasing/decreasing slightly” for records not meeting the 95% confidence interval, but meeting the 90% confidence interval (p-values between 0.1 and 0.05). This category was created to better track sample records that are exhibiting a movement towards a significant trend. Some time-series records may exhibit seasonal trends. As such, a seasonal MK trend analysis may be appropriate. Due to the inconsistent sampling frequencies encountered, however, seasonal MK analyses were not conducted. Finally, for records with identified trends, a Theil-Sen (TS) estimator was applied to estimate the slope of the trend. For a more thorough discussion on MK, seasonal MK tests, and TS estimation, refer to the ProUCL Technical Guide (EPA, 2022). As the sampling frequency was converted to quarters, the output of the TS estimation is a slope that equals the estimated rate of change per quarter for each assessed trend. These slopes were multiplied by four to calculate an estimated annual change in chloride concentration as shown in Appendix A: Tables A.4 and A.5. These estimated rates of change were used to proportionally display trends in Figures 48b and 49b.

A potential source of error or bias in this study stems from water introduced to the formation during drilling and well construction activities. When drilling, external waters can be introduced into the formation through drilling mud or through direct addition of water into the borehole. The chemical composition of these introduced waters can be markedly different from the ambient formational groundwater. Subsequent sampling or purging efforts can remove these non-ambient waters, leading to an apparent increase in chloride concentration where none actually has occurred in the formation. It can often take multiple purging events to fully remove the introduced fresher or saltier water. Figure 51 exhibits this concept in well 60C 67 where early fresh samples are likely introduced during drilling and not representative of the natural formation groundwater. Removal of these early samples provides a potentially less biased record of ambient groundwater chemistry.

Data patterns within time-series commonly evolve in response to changing conditions and variables. The most appropriate analytical time frame depends on the objective. In this study the complete data records are analyzed as the purpose of this study is to identify overall regional trends. If, however, the objective were to analyze the groundwater system response to a known perturbation (such as a sharp reduction of a large water withdrawal), the period of analysis could be adjusted.

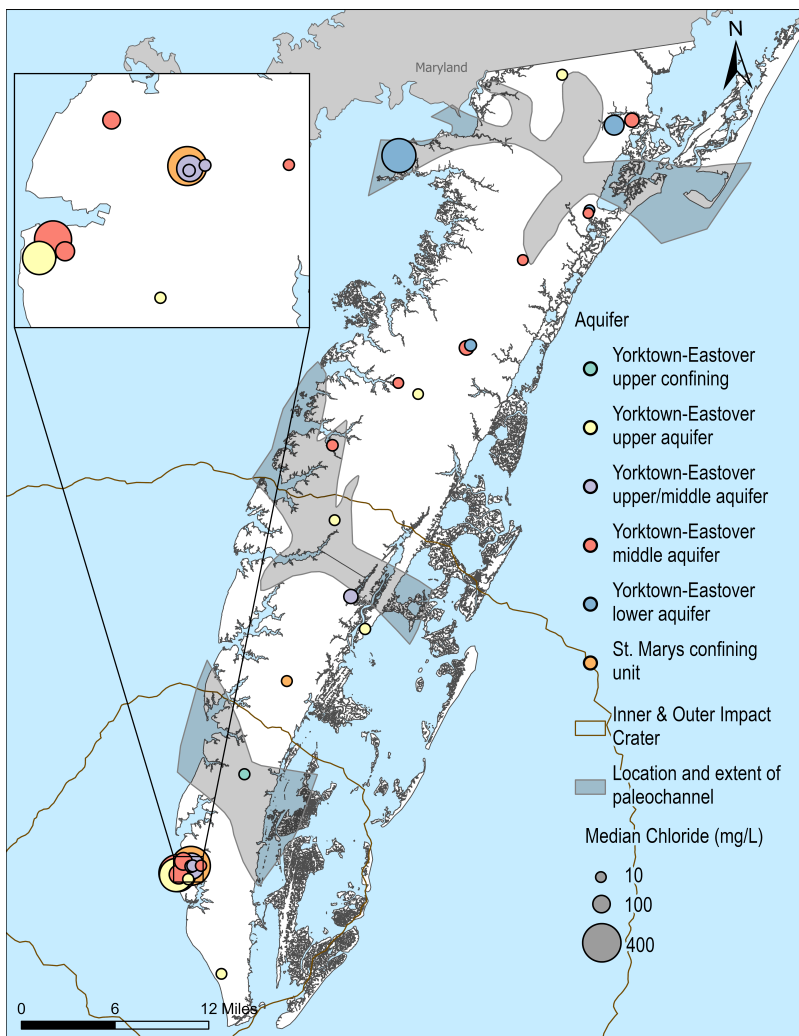


(a) Eastern Virginia sites where chloride records were sufficient for trend analysis. Locations are colored by aquifer and scaled to median chloride concentration (mg/L).

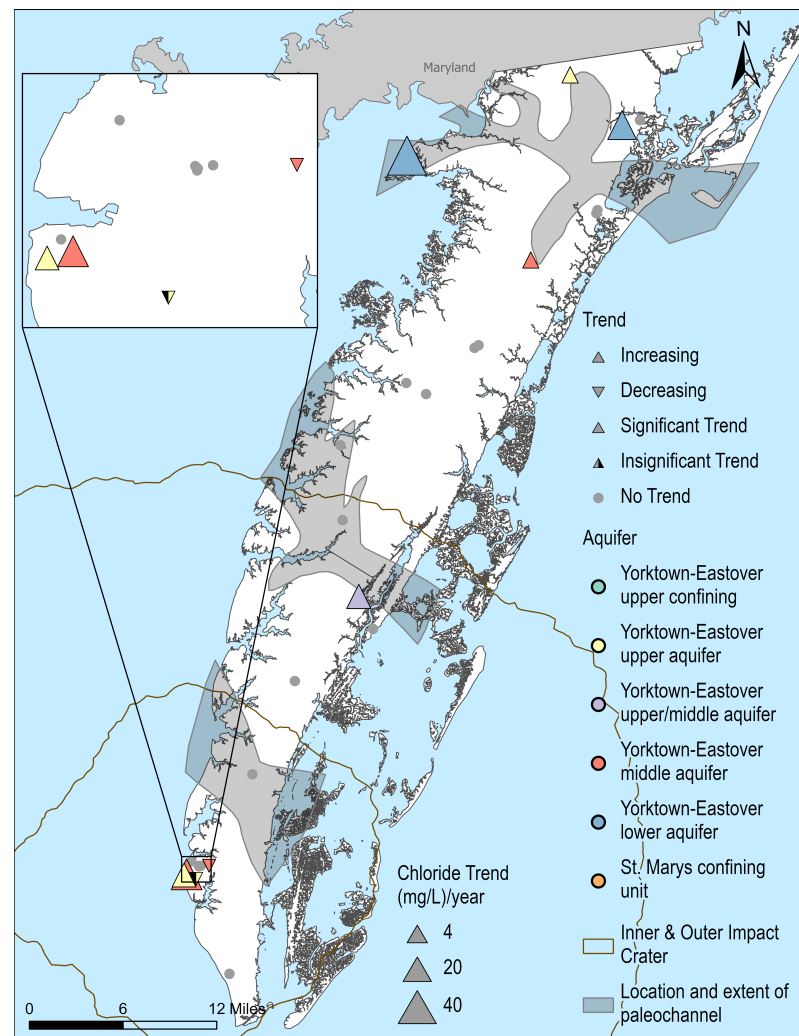


(b) Eastern Virginia sites where a trend was present, statistically significant or otherwise. For sites with a trend, symbology is colored by aquifer, indicates significance, is oriented to indicate direction of trend, and is scaled to slope (mg/L/yr).

Figure 48: Distribution of Eastern Virginia groundwater records analyzed for trend in map view. Symbol size represents median chloride concentration. Northward-pointing triangles indicate increasing trends, southward-pointing triangles indicate decreasing trends, and dots indicate no trend. Symbol color indicates aquifer.



(a) Eastern Shore sites where chloride records were sufficient for trend analysis. Locations are colored by aquifer and scaled to median chloride concentration (mg/L).



(b) Eastern Shore sites where a trend was present, statistically significant or otherwise. Symbolism is colored by aquifer, indicates significance, is oriented to indicate direction of trend, and is scaled to slope (mg/L/year).

Figure 49: Distribution of Eastern Shore groundwater records analyzed for trend in map view. Symbol size represents median chloride concentration. Northward-pointing triangles indicate increasing trends, southward-pointing triangles indicate decreasing trends, and dots indicate no trend. Symbol color indicates aquifer.

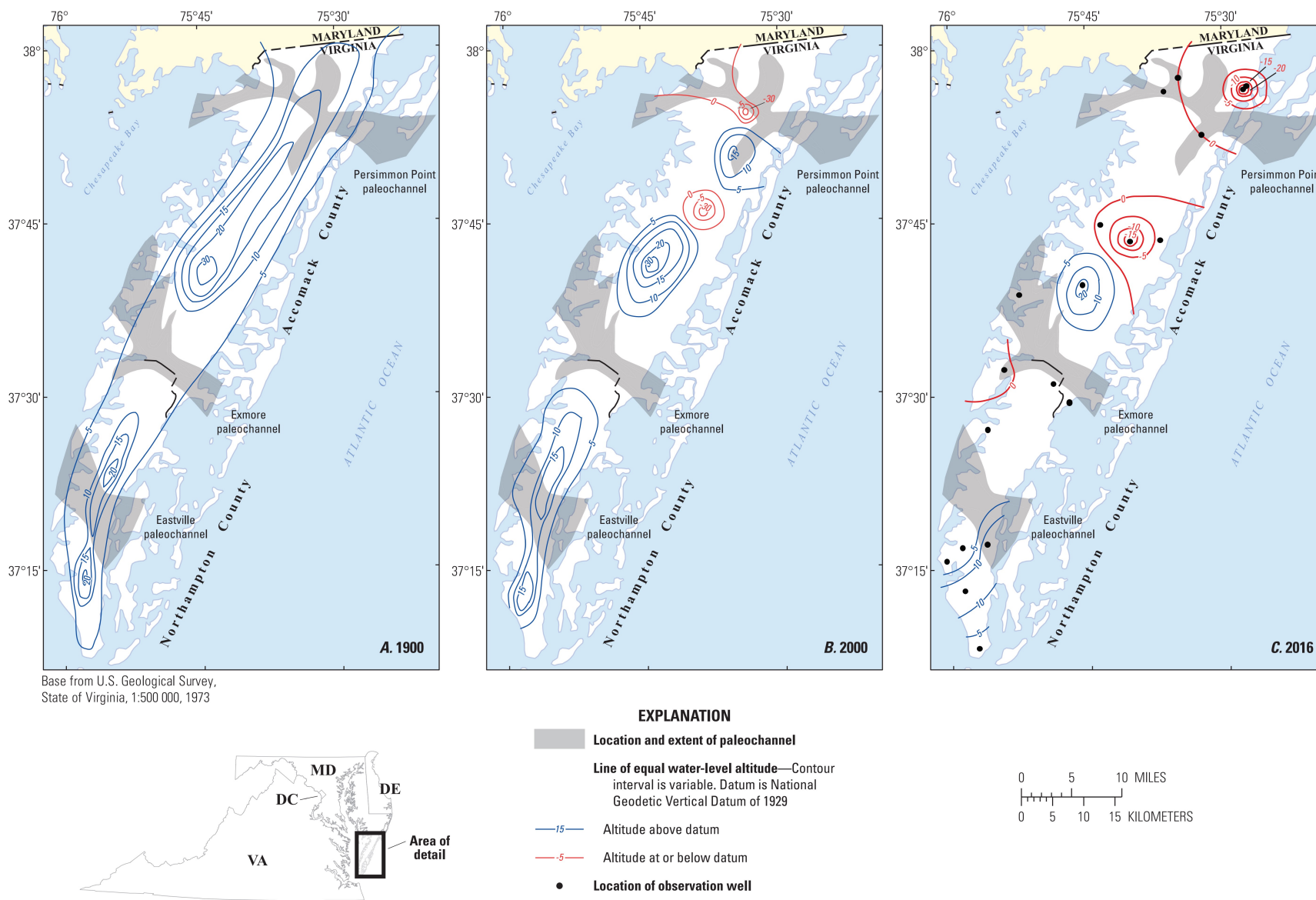


Figure 50: Generalized groundwater levels in the Yorktown-Eastover aquifer system on the Virginia Eastern Shore: A, 1900 (simulated); B, 2000 (simulated); C, 2016 (observed). Water levels integrated among upper, middle, and lower aquifers. Reproduced from [McFarland and Beach \(2019\)](#).

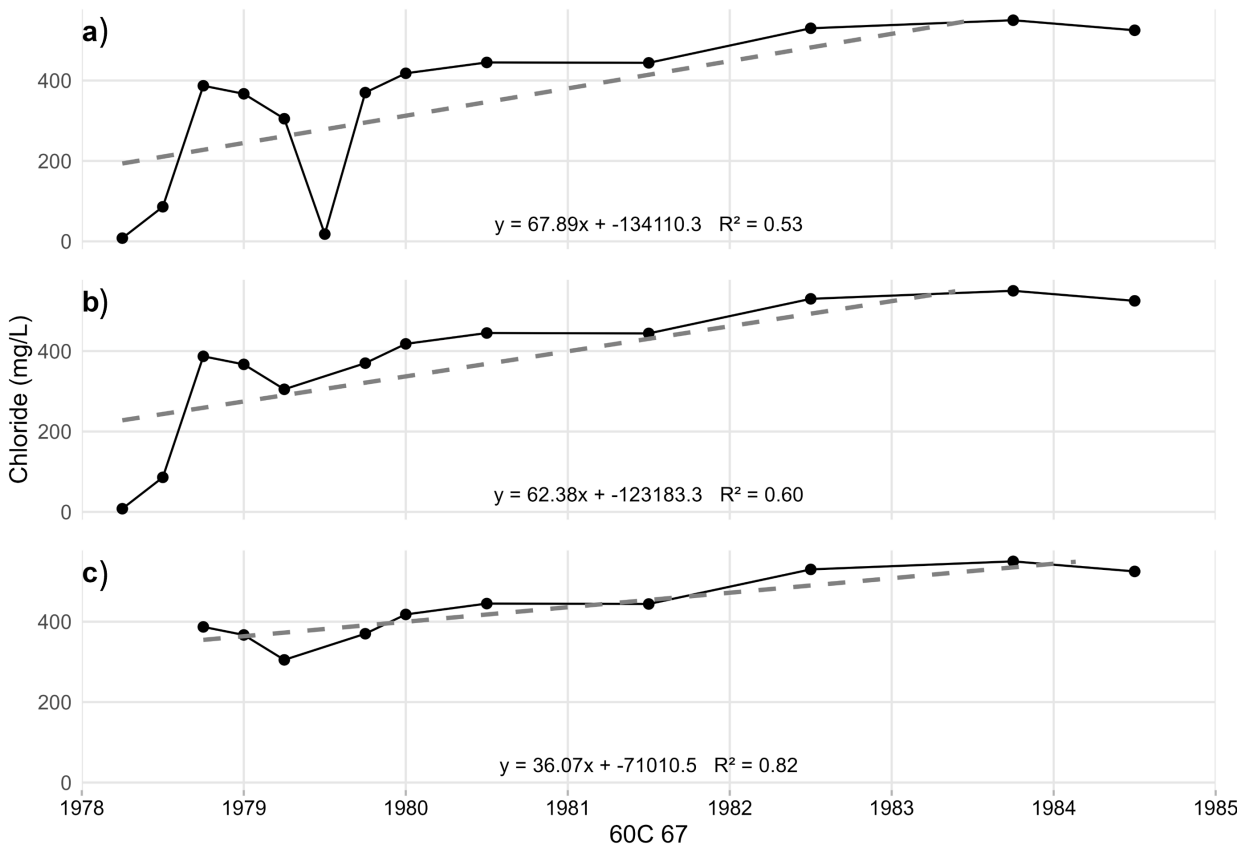


Figure 51: Plot of 60C 67 illustrating the possible introduction of non-formational (in this case fresher) water during drilling and the subsequent removal of freshwater biasing during sample purging. Inclusion of earlier samples could result in false trend identification and(or) misleading rates of change.

3.5.2 Results and Discussion

Key Point #4 (repeated)

These conditions cause land subsidence (sinking) and the potential for regional saltwater intrusion (saline water moving into freshwater aquifers). **Chloride concentrations in the aquifer system are increasing locally in some parts of Eastern Virginia and on the Eastern Shore.** See also Section 1.4.4.

A summary of the 103 trend analyses completed for the mainland VCP (N = 75) and the Eastern Shore (N = 28) is provided in Table 12. No trend was identified in 69% of locations while 31% (32 locations) exhibited a statistically significant trend (25 locations, p-value < 0.05, 95% confidence) or slightly increasing/decreasing trend (7 locations, p-value < 0.1, 90% confidence). The breakdown of each analysis for the mainland VCP and the Eastern Shore is provided in Appendix A: Tables A.4 and A.5, respectively.

Based on mapped rates of chloride concentration changes, McFarland (2010) identified two broadly fan-shaped areas of elevated changes flanking the outer rim of the impact crater (Figure 39). The first such fan extends across the York-James and Middle Peninsulas, extending east and south; and the second along much of the area south of the James River, including Southampton County and extending east and northeast across cities of Suffolk, Chesapeake, Portsmouth, and Norfolk. The trends identified in this study tend to align well with the greatest rates of change in chloride concentrations shown in Figure 39 as presented by McFarland (2010). Like the increasing rates of change, the increasing trends appear to coincide with the

leading edge of the saltwater-transition zone along the edge of the Chesapeake Bay impact crater. While the trends presented in this work do not fully delineate these broad fan-shaped regions, the trends identified do support their relative locations (Figures 48 and 49) (McFarland, 2010).

Table 12: Summary of Chloride Concentration Trend Analyses

Trend and Significance	Mainland	Eastern Shore	Overall
Statistically Significant Increasing Trend	13 (17%)	7 (25%)	20 (19%)
Statistically Significant Decreasing Trend	4 (5%)	1 (4%)	5 (5%)
No Significant Trend	52 (69%)	19 (68%)	75 (69%)
No Significant Trend, increasing slightly	6 (8%)	0 (0%)	6 (6%)
No Significant Trend, decreasing slightly	0 (0%)	1 (4%)	1 (1%)
Total Records Analyzed	75	28	103

Mainland Virginia Coastal Plain

Of the 75 mainland VCP records analyzed for trend, 13 have statistically significant increasing trends (p-value < 0.05) and six exhibit slightly increasing trends (p-value < 0.1). Very few trends were detected within the shallow aquifer systems. Two records, 59B 39 and 63A 2, are associated with the surficial aquifer in the northern Dismal Swamp and the City of Virginia Beach, respectively. The former, 59B 39, exhibits a statistically significant decreasing trend that is likely highly influenced by local precipitation. The latter, 63A 2, exhibits a slightly increasing trend in chloride that is potentially associated with de-watering activities occurring at a borrow pit located approximately 0.25 miles west of the well.

Records from two wells screened in the Yorktown-Eastover aquifer, 59G 19 and 60C 67, were found to exhibit statistically significant increasing trends. Both records exhibit fairly steep slopes (Appendix A: Table A.4), indicating a broad continuous increasing trends. These two wells adjacent to Sarah Creek and the Elizabeth River, respectively; which are tidal-influenced brackish water systems that are very likely the primary cause of the increasing chloride trends. These records are similar to the that of 60C 61 identified by McFarland (2010), who found that the well exhibited a sustained and substantially increasing trend caused by localized intrusion from the tidal brackish water embayment of the James River. This well was not included in the current assessment as the data did not pass the acceptance criteria utilized in this study.

McFarland (2010) also found that well 58F 50 SOW 171A, in the City of Newport News, exhibited a “broad pattern of concentration change”. A statistically significant trend for 58F 50 SOW 171A was also identified in this study. This increasing trend fits within the broad fan of high rates of change identified on the York-James Peninsula (McFarland, 2010). Broad patterns of concentration change could possibly be an artifact of relatively low-frequency sampling and were the sampling frequency to be increased, a “punctuated pattern of concentration change” attributable to upconing could be revealed (McFarland, 2015). Infrequent sampling can also result in the identification of false trends as illustrated in Figure 52. Examples of broad and punctuated patterns of concentration change overlying an increasing trend is shown in Figure 53.

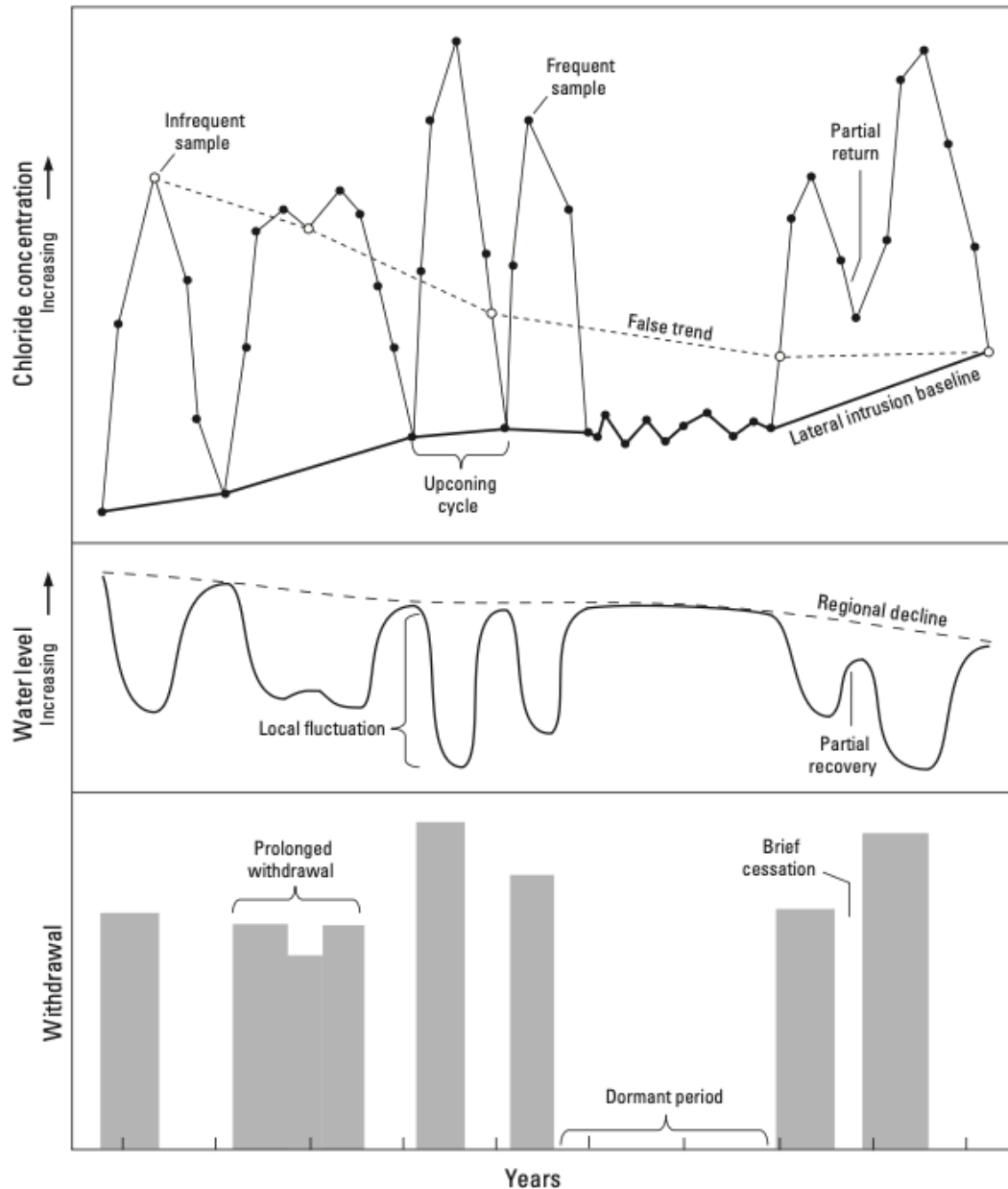


Figure 52: Generalized temporal relations between groundwater chloride concentrations, water levels, and withdrawals. Arbitrary units. Chloride concentration response to changing water levels and withdrawals highlighted. Lateral intrusion monitoring is linked to baseline concentrations. Upconing cycles controlled by withdrawals and water level fluctuations. Frequent samples (black dots) can be helpful in distinguishing upconing from lateral intrusion, while infrequent samples (open dots) can produce a false chloride trend (McFarland, 2015).

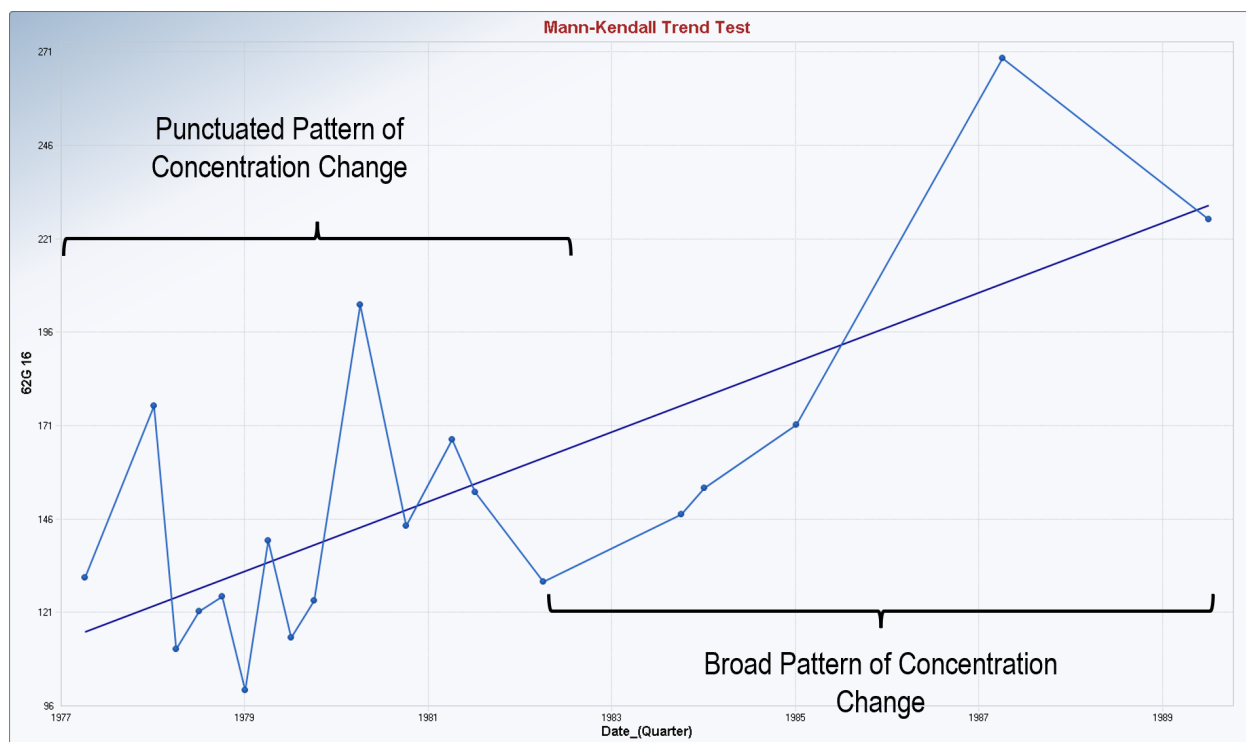


Figure 53: Example Mann-Kendall Trend plot of 62G 16 in Northampton County exhibiting both punctuated and broad periods of concentration change. The increasing trend exhibited by this record is statistically significant (EPA, 2022).

Figure 48b presents the distribution of identified trends proportionally sized to reflect their slope or rate of change. Many trends within the Potomac aquifer are clustered along the leading edge of the saltwater-transition zone and exhibit punctuated (upconing) patterns of concentration change in response to nearby withdrawals. Two of these significant increasing trends are identified in the Northern Neck, but both exhibit very gradual slopes indicative of very small changes in overall chloride concentrations (Figure 48a). One well, 60L 24, is associated with a long-term withdrawal in the Town of Reedville. The second well, 59K 30, is located in the Town of Irvington and sits between three community water systems. A slight increasing trend was identified in well 57A 8 in the Village of Whaleyville. This well was sampled in the mid-1970s to mid-to-late 1980s and was likely a production well for the Village. Chloride concentration trends in these wells likely reflect upconing, but the concentrations and estimated rates of change are low.

Wells 60C 35, 60C 70 and 60C 71 are located in the City of Portsmouth. These wells were formerly part of a groundwater supply system associated with now-defunct facilities that were located near the position of the saltwater-transition zone. While the historic estimated trend slopes for these wells indicated a rapid change, the actual rate presumably decreased with the cessation of local withdrawals. An additional well in Portsmouth, 59C 33, associated with a current permitted withdrawal exhibits a slightly increasing trend. Given the chloride concentration for the period of record (mean = 154.5 mg/L; median = 148.5 mg/L; 1981–1987), the moderate steepness of the estimated slope, and the continued withdrawals; the chloride concentrations may be approaching the federal secondary maximum contaminant level of 250 mg/L.

Significant increasing trends were identified in three wells within the trend well network regularly sampled by DEQ. From south to north, these wells are 59D 25 SOW 213, 58F186 SOW 244, and 57F 36. Each of these wells is associated with, and located within a few hundred feet of a permitted groundwater withdrawal. Water-quality monitoring will continue at these wells to maintain a water quality baseline along a transect of the York-James Peninsula.

Two records in King and Queen County, 56J 11 SOW 073 and 57J 3 SOW 074, exhibit increasing trends. The slopes for these trends are low and indicate a very small increase over the course of the record (approximately 50 years). Groundwater withdrawals at the West Point Mill are spatially associated with

these increasing trends. Well 56J 5, a former production well in West Point, exhibits a sharply increasing statistically significant trend for the period of 1978–1987. This topic is discussed in more detail in Section 3.5.2.

Two wells, 59C 48 in the City of Suffolk and 58D 1 in Isle of Wight, exhibited slightly increasing chloride trends (p -value < 0.1). These wells were sampled between the mid-1970s and the to mid-to-late 1980s. These wells have low chloride concentrations with low slopes and are of little concern. No known significant groundwater withdrawals are recognized with 58D 1 and 59C 48 during their periods of record.

Three records, 57D 8, 56C 1, and 58C 35, exhibit statistically significant decreasing trends in chloride concentration. Well 57D 8 is located in the Town of Smithfield and near a currently inactive production well. However, the decreasing trend occurred during the period when the nearby production well was active. This well is located in an area with anomalous salinity concentrations. The remaining two wells, 56C 1 and 58C 35, are not associated with known production wells. Review of records and construction suggest that the trend in 56C 1 may be reflective of ambient conditions. Additionally, a similar review suggests the trend in 58C 35 may be reflective of a chloride spike introduced during drilling activities. Regardless, while the trends were identified as statistically significant, the water quality associated with these wells is excellent and not necessarily improving as evidenced by the very low chloride concentrations and shallow slopes estimated by the TS analysis.

The trend analyses reported here represent a preliminary assessment of the available data. Comparing these time series with associated local withdrawals and water levels would be required for a more complete assessment. Many of these ancillary data types are difficult or impossible to obtain, which could preclude such an investigation. A subset of the wells assessed in the report are examined more thoroughly in Section 3.5.2. The current assessment does identify localized responses in chloride concentrations to associated proximal groundwater withdrawals and broadly confirms the conclusions outlined by [McFarland \(2010\)](#).

Eastern Shore

Groundwater salinity in the Eastern Shore increases with depth, and water withdrawals from depths less than 300 feet BMSL typically have chloride concentrations <250 mg/L. This depth and chloride concentration relationship is generally true for the Eastern Shore wells identified as suitable for trend analysis (Appendix A: Table A.5). The only exception is well 65M 3 in Accomack County screened in the lower Yorktown-Eastover aquifer. This well is screened shallower than 300 feet BMSL but exhibits chloride concentrations >250 mg/L. The relationship holds true for most of Northampton County but not in the area of Bayshore Concrete and Cape Charles, along the southwestern margin of the Eastern Shore. In the Cape Charles area, substantial withdrawals are spatially associated with well-documented elevated chloride concentrations ([Richardson, 1993](#); [Nowroozi et al., 1999](#); [Sanford et al., 2009a](#); [McFarland and Beach, 2019](#)). The Town of Cape Charles and the Bayshore Concrete facility are located on the coast and near the boundary between fresh and saltwater. Groundwater flow paths along this boundary are shorter relative to the middle of the peninsula. Groundwater levels depicted in Figure 50 suggest that the hydraulic gradient configuration in the area of Cape Charles may not be conducive to lateral migration of saltwater; therefore upconing is a likelier source of increasing chloride concentrations in this area.

In total, 28 records were suitable for trend analysis, with an overall average mean and median chloride concentration of 102.8 and 98.8 mg/L, respectively. Accomack County has 12 records with an average mean and median of 68.1 and 62.3 mg/L, while Northampton County has 16 records with an average mean and median of 128.8 and 126.1 mg/L. Northampton County's chloride concentrations are higher. The discrepancy may stem from the location and depth of the water sample records; the Accomack County sample locations tend to be along the spine of the Eastern Shore, whereas the Northampton County sampling locations tend to be closer to the coast. The distribution of rates of change (slopes) related to identified trends is provided in Figure 49. Trends are clustered in northern Accomack County, where they are aligned with the Persimmon Point Paleochannel and where groundwater levels are below sea level (Figure 50); and in southwest Northampton County in the vicinity of Cape Charles. For trend records within the former, aquifer designations may need to be redefined in the context of the two confined paleochannel aquifers described by [McFarland and Beach \(2019\)](#).

In Accomack County, four of twelve records show a statistically significant increasing trend in chloride concentrations. These records span approximately 8–11 years, straddling 1980. It is unknown whether these

trends have persisted to the present day. Three of the four increasing chloride trends in Accomack County align well with portions of the Persimmon Point Paleochannel (Figure 49). These trends may be influenced by the groundwater dynamics associated with paleochannels in which higher hydraulic conductivities act to drain and lower groundwater levels that then draws the saltwater-transition zone upwards (McFarland and Beach, 2019). An increasing trend is identified in 65M 3 in Saxis, where trends are likely exacerbated by the abrupt shallowing of the saltwater-transition zone along the coast. The two remaining increasing trends associated with the northernmost paleochannel are 66L 6 in Bloxom and 66M 22 north of New Church.

The last statistically significant increasing trend in Accomack is associated with 67M 9 at the National Aeronautics and Space Administration (NASA) Wallops Flight Facility in Chincoteague. This location exhibits one of the steepest trends in Accomack County. The depth and position of this well near the Atlantic Ocean place it in proximity to the abrupt saltwater-transition along the margin. The well construction, location, and water withdrawals associated with the NASA facility increase the potential for localized saltwater intrusion. Previous studies have documented a decline of groundwater levels below sea level in this area, which has seen a reversal of the predevelopment hydraulic gradient (Figure 50). Due to the limited historical sampling period, it is unknown whether the chloride concentration trend has persisted to the present day.

Three wells in southwest Northampton County exhibit significant increasing trends. Two wells, 62G 27 and 62G 16 near the Bayshore Concrete facility, are screened in the upper and middle Yorktown-Eastover aquifer, respectively. The deeper well, 62G 16, has a 12-year period of record (1977–1989) and mean/median chloride concentrations of 152.8/144 mg/L. The estimated slope of the trend for 62G 16 is steep, with an estimated increase of nearly 35 mg/L per year over the period of record. The shallower well, 62G 27, has a 7-year period of record (1999–2006) and mean/median chloride concentrations of 365.9/369 mg/L. The estimated slope for 62G 27 is about half that of 62G 16. This facility has numerous active and inactive groundwater production wells that have been presumably supplying water for decades. Located along the southwestern coast of the Eastern Shore, it is subject to upconing and mixing with the shallower saltwater-freshwater interface.

Two additional wells in southwest Northampton County show slightly decreasing chloride concentrations (p -value < 0.1). The period of record is short (2004–2006), and both locations are associated with the Cape Charles. Chloride concentrations are low (<20 mg/L), and the decreasing trend may be due to a reduced water use over the period of record due to increased precipitation. Northampton County's 2003–2006 precipitation (51.9 inches) represents a 22.7% increase over the region average and suggests this as a possibility (NOAA, 2025).

A significant increasing trend is identified in well 64J 25, along the eastern margin of the Eastern Shore in Willis Wharf. This well is screened in both the upper and middle Yorktown-Eastover aquifers. The well has a 10-year period of record (1978–1987) and mean/median chloride concentrations of 64.56/66 mg/L. The nearest permitted withdrawals are about 1.5 miles inland to the southwest, west, and north. The likely source is localized intrusion from the abruptly shallowing saltwater–freshwater interface associated with the Eastern Shore coast and possibly the hydraulic influence of the Exmore Paleochannel.

Overall, the information presented in this section suggests a spatial association of increasing chloride trends with nearby groundwater withdrawals on the Eastern Shore, especially where the withdrawals occur in proximity to the coast and the saltwater-transition zone. These observations are generally consistent with the results of the regional groundwater budget analyses that indicated flow upward from the St. Marys confining unit underlying the Yorktown-Eastover system, as well as small rates of inflow from coastal water bodies (Section 2.4.3). Detailed local characterization would be required to determine the specific causes of the increasing trends, the scale of saltwater migration, and the relative contributions of potential upconing and potential lateral migration to the overall movement of saltwater in the aquifer system.

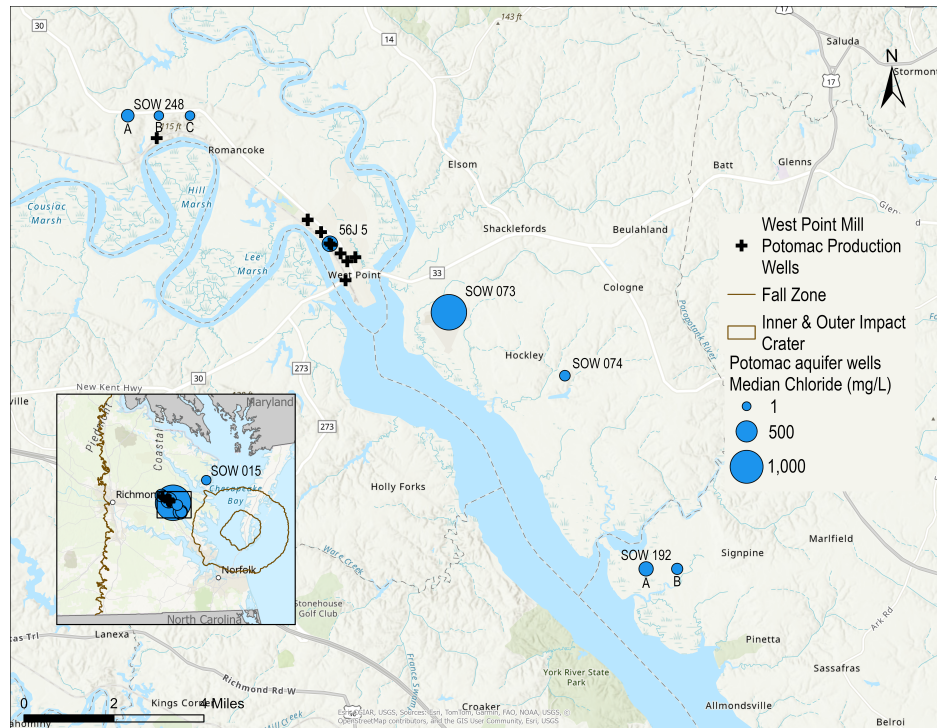
Case Study: West Point Mill Withdrawal

The WestRock Paper Mill (the Mill) in West Point, Virginia, is one of the largest permitted users of groundwater in the VCP. Pursuant to permit special conditions for the Mill, groundwater levels and quality are monitored through a network of monitoring wells. Groundwater quality is monitored through annual sampling of twelve wells screened in the Potomac aquifer, as depicted in Figure 54. These water-quality wells transect the Middle Peninsula and include a single well in the eastern Northern Neck. A three-well nest screens the upper, middle, and lower zones of the Potomac aquifer approximately 5 miles northwest of the Mill (55J 15 SOW 248A, 55J 16 SOW 248B, and 55J 17 SOW 248C). Within the Mill footprint, three monitoring wells are screened in the Potomac aquifer (56J 42 SOW 247A, 56J 43 SOW 247B, and 56J 44 SOW 247C). Approximately 2.5 miles east-southeast of the Mill is 56J 11 SOW 073, screened in the lower zone of the Potomac aquifer. Approximately 5.5 miles east-southeast of the Mill is 57J 3 SOW 073, screened in the middle zone of the Potomac aquifer. Approximately 10 miles southeast of the Mill is a multi-well nest: 57H 20 SOW 192A screened in the middle zone of the Potomac aquifer, 57H 21 SOW 192B screened in the upper zone of the Potomac aquifer, and 57H 22 SOW 192C screened in the overlying Aquia aquifer. About 26 miles northeast on the Northern Neck, 59K 1 SOW 015 is the most distal monitoring point.

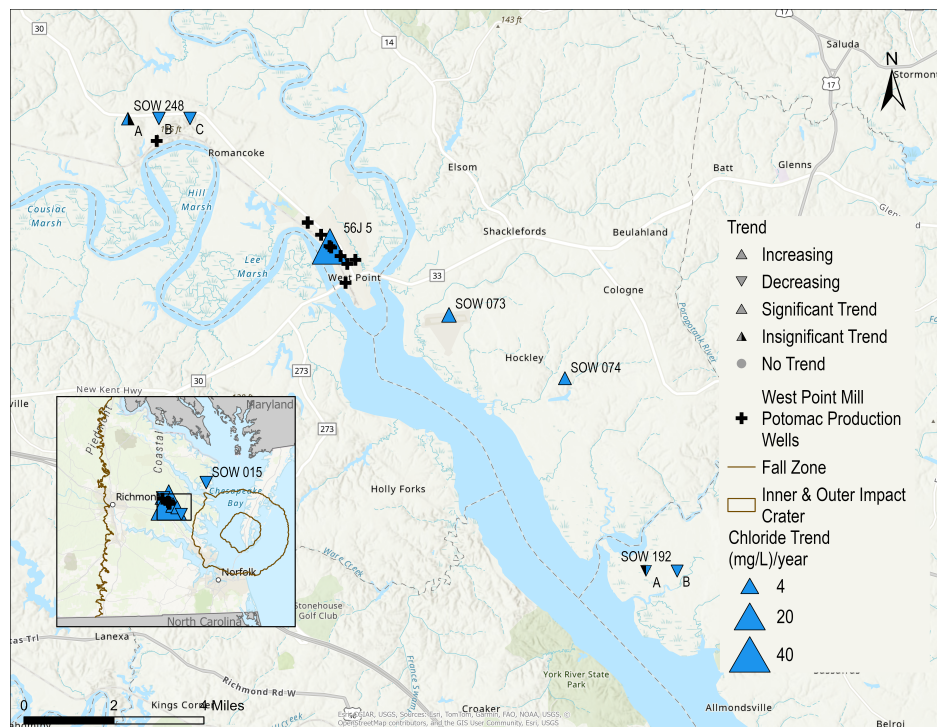
Historically, these wells were sampled quarterly, providing a wealth of water-quality data for the region. Nine of 12 wells have sufficient sampling history for trend analysis. A former production well (56J 5; Fort Street Well) also has a history of water-quality sampling useful for trend analysis, providing an analog for production well trends. However, chloride concentrations from this abandoned well are unlikely reflective of current groundwater concentrations at the Mill due to the age of the well, sampling period, and general well design differences. The well nest within the Mill footprint does not yet have sufficient data to effectively analyze trends. The former production well, 56J 5, presents a statistically significant increasing trend in chloride concentrations from 1978 to 1987. Using data obtained from the WQP, chloride records for 56J 11 SOW 073 (1973–2019) and 57J 3 SOW 074 (1970–2019) exhibit increasing trends, with the former being statistically significant. 59K 1 SOW 015 (1972–2006), however, shows a statistically significant decreasing trend with concentrations <25 mg/L.

The Mill reports water quality results to DEQ that are not available through the EPA WQP, or associated repositories such as NWIS and STORET. When analyzing high resolution chloride concentration records from the Mill, significant increasing trends are further confirmed for 56J 11 SOW 073 and 57J 3 SOW 074 (Figure 55; Table 13). Mapping of these trends in Figure 54, indicates a spatial association with the Mill withdrawals' area of impact.

The more distant wells at SOW 192A and -B exhibit decreasing chloride concentrations. If regional scale intrusion not associated with withdrawals were occurring, the trends in these wells would presumably be increasing. The primary difference is that the period of record for the SOW 192 wells of 2004–2024, is more recent than the records of 56J 11 SOW 073 and 57J 3 SOW 074. Applying a truncated period of record of 1995–2024 to wells 56J 11 SOW 073 and 57J 3 SOW 074, results in the stabilization of chloride concentrations and the loss of significant trends (Figure 55). The remaining wells primarily exhibit a decreasing trend in chloride concentrations. The decreasing trends in SOW 248B and -C may be due to their distance from the Mill, or their position to its west, where any potential influence of withdrawals on groundwater flow would increase the component of freshwater. Increasing chlorides in the deeper SOW 248A, however, could result from localized upconing. In any case, a spatial association exists between the Mill withdrawals' area of impact and the chloride trends identified within the Mill's monitoring network.



(a) West Point Mill area monitoring sites where chloride records were sufficient for trend analysis. Symbology is scaled to median chloride concentration (mg/L). Production wells are shown.



(b) West Point Mill area monitoring sites where a trend was identified, statistically significant or otherwise. For sites with a trend, symbology indicates significance, is oriented to indicate direction of trend, and is scaled to magnitude of trend (mg/L/year).

Figure 54: West Point Mill groundwater monitoring network illustrating trends in chloride concentrations when accounting for reported permit-required samples (see also Table 13). Inset figures are scaled to include the distal SOW 015.

Table 13: Chloride Trends Derived from Alternative Data Sets, West Point Area

USGS Local No.	Trend from WQ Portal Data (N)	Trend from Permittee Data (N)	Date Range	Median Chloride (mg/L)	Theil-Sen Slope (mg/L/yr)
55J 15 SOW 248A	–	Increasing slightly (21) ²	2004–2024	121.2	1.616
55J 16 SOW 248B	–	Decreasing (59) ¹	2000–2024	3.3	-0.08
55J 17 SOW 248C	–	Decreasing (20) ¹	2000–2024	2.5	-0.1
56J 5	Increasing (11) ¹	Increasing (6) ¹	1978–1987	234	32
56J 11 SOW 073	Increasing slightly (19) ²	Increasing (74) ¹	1973–2024	978.7	2.836
57H 20 SOW 192A	–	Decreasing slightly (58) ²	2004–2024	188.1	-1.104
57H 21 SOW 192B	–	Decreasing (58) ¹	2004–2024	70.7	-0.776
57J 3 SOW 074	Increasing (19) ¹	Increasing (76) ¹	1970–2024	48.2	0.54
59K 1 SOW 015	No Trend (11)	Decreasing (63) ¹	1972–2024	2.4	-0.162

West Point area trends of Water Quality Portal data with and without permit required data.

¹ Statistically significant trend.

² Not a statistically significant trend.

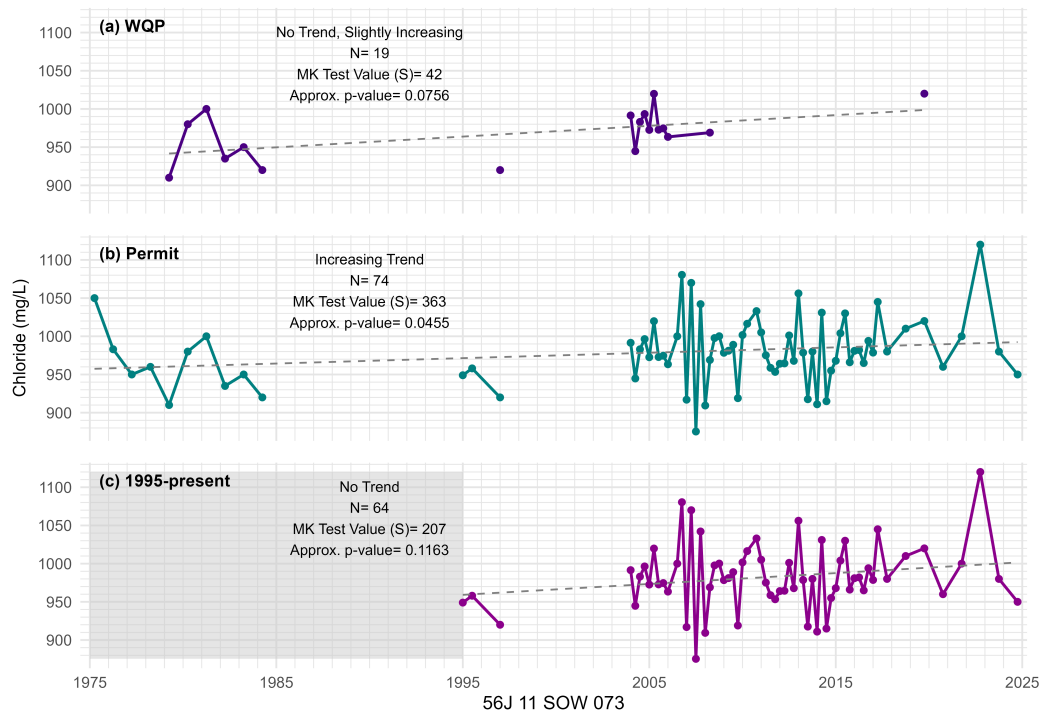


Figure 55: Plots of 57J 11 SOW 073 displaying differences in trend significance given select time frames and data sets. For all plots, samples are indicated by points, and those within three years of each other are connected. MK trend analysis values are shown for each, and a linear gray dashed-line of best fit is shown. All plots share a common x-axis and have uniform scaling on their respective y-axis. **(a)** WQP data only. **(b)** WQP data supplemented with permit condition sampling by the West Point Mill. **(c)** WQP and permittee chloride trends for samples following the Ground Water Management Act of 1992.

3.6 Groundwater Quality: Summary

This work has built upon that of [McFarland \(2010\)](#) in updating and expanding a large VCP water-quality data set that provides local- and regional-scale information on groundwater quality for well drillers, landowners, consultants, and resource managers. A comparison of groundwater quality for the period of 1906–2007 and 2007–2024 demonstrated that regional groundwater quality has been stable since 2007 and further supported the previous finding that groundwater quality has been largely stable since the first samples were collected in the early part of the 20th century ([McFarland, 2010](#)).

Updated cross-sections indicated that recent data were consistent with the vertical spatial trends in groundwater quality and regional-scale processes, such as differential flushing, described by [McFarland \(2010\)](#). Plotting of water types indicated that the general regional extent of the saltwater-transition zone remained virtually unchanged since 2007. Piper trilinear diagrams indicated that the evolution and extent of hydrochemical facies remained consistent with those described by [McFarland \(2010\)](#). Finally, broadly applied trend analysis found no regionally extensive significant trends in groundwater chloride concentrations.

The new groundwater-quality analysis did identify locally increasing chloride concentrations. These trends were typically associated with neighboring withdrawals or, in the case of the West Point Mill, a larger-scale withdrawal having a wider area of impact. The affected locations were mostly along shallow parts of the saltwater-transition zone, in the region adjacent to the outer rim of the impact crater and along the coasts of the Eastern Shore. These findings were consistent with the overall groundwater-quality data and trends identified in the VCP by [McFarland \(2010\)](#), in the Eastern Shore model by [Sanford et al. \(2009a\)](#), within paleochannels by [McFarland and Beach \(2019\)](#), and in DEQ annual simulation reports ([DEQ, 2024a](#)). The findings were also consistent with evidence from the regional groundwater budget analyses, presented above.

The trend analysis was applied to each well that offered a suitable data set, regardless of the sample period; therefore, the results included wells that exhibited trends in the past, as well as in the present day. Some locations with increasing trends, notably near Chincoteague on the Eastern Shore and near West Point in Eastern Virginia, coincided with areas where known withdrawals have caused groundwater levels to decline below sea level, creating conditions that would favor lateral saltwater intrusion. However, even under favorable conditions, lateral migration may be delayed significantly by the generally slow rate of groundwater flow. For these reasons, it was difficult to distinguish whether the observed local trends were transitory, as opposed to indicating a potentially broader, long-term shift in the regional saltwater-transition zone. In the future, aquifer-replenishment operations such as SWIFT may cause significant groundwater-level changes that could also induce local or regional changes in aquifer salinity. DEQ's chloride-monitoring strategy, developed in cooperation with USGS, is designed to collect new data for additional evaluation of these issues (Section 1.4.5).

4 Regulatory Framework

Key Point #8

The Ground Water Management Act of 1992 has achieved mixed results. The regulatory framework enabled the Commonwealth to stabilize groundwater-level gains that resulted from the unrelated closure of the Franklin Mill in 2010. However, groundwater supply east of I-95 is constrained, and current projections indicate declining availability in the near future.

4.1 Effectiveness of the Ground Water Management Act of 1992

As described in Section 1.3 of this report, the goal of the Ground Water Management Act of 1992 is to provide for the long-term preservation of groundwater supply. The primary mechanisms through which the Ground Water Management Act of 1992 regulates groundwater withdrawals is to establish a mechanism by which groundwater management areas (GWMAs) are declared in regulation, and then by requiring withdrawals greater than 300,000 gallons in any one month to obtain a permit, unless otherwise exempted.

The Ground Water Management Act of 1992 provided the framework to establish the Eastern Virginia GWMA and the Eastern Shore GWMA. Collectively, these two areas cover most of the Commonwealth east of Interstate 95. DEQ currently administers 378 groundwater withdrawal permits in these two GWMAs. The Ground Water Management Act of 1992 and its implementing regulations also provided the framework that enabled DEQ to undertake the VCP Groundwater Initiative from 2014 and 2017 to negotiate lower permitted withdrawal limits for the top 14 largest permitted groundwater withdrawers in the Eastern Virginia GWMA.

As noted in Section 2 of this report, the effectiveness of the Ground Water Management Act of 1992 is mixed. Whether a result of the permitting framework, the reduction in Franklin Mill withdrawals, the VCP Groundwater Initiative, or a combination of the three, in many areas water levels stabilized during the past decade. This shows that regulation can and does have a measurable effect on groundwater trends.

However, that effect is currently somewhat limited, and more recent observation data indicates that water levels may be starting to decline again. As mentioned in Section 2.3.2 of this report, groundwater levels across the important Potomac **aquifer** mostly have stalled or begun to decline. Figures 25 and 28 show these conditions come after a period of modest gains in the regional groundwater level between 2010 and 2021. From 2021 to 2024, at each of seven trend-monitoring locations, the rate of increase of groundwater levels either slowed significantly or reversed altogether and went into a decline. If this regression goes unaddressed, it may lead to effects such as compaction, land **subsidence**, saltwater **intrusion**, and, eventually, the loss of groundwater resources.

While the fate of the VCP aquifer system is yet uncertain, DEQ is confident that the system cannot currently support further large-scale withdrawals. Figure 37 in Section 2.5.3 above shows that a large-scale economic development project could not pass the technical evaluation in the majority of the VCP. This means that throughout most, if not all, of eastern Virginia, groundwater resources are unavailable to support any significant future growth or economic development.

4.2 Identified Issues and Recommendations

The following are 8 key problem areas this study revealed and DEQ's 12 associated recommendations to address them.

4.2.1 Lack of Groundwater Supply for Future Withdrawals in the VCP

One of the more serious conclusions of DEQ's joint study with USGS is that there is virtually no capacity in the VCP aquifer system to support additional permitted significant withdrawals. Withdrawals in a GWMA of 300,000 or more gallons in any one month must obtain a groundwater withdrawal permit. In order to receive a groundwater withdrawal permit, the withdrawal must pass a technical evaluation. As demonstrated in Section 2.5 of this report, the maximum withdrawal amount that would pass a technical evaluation in the

best-case location was 360,000 gal/day, an amount far less than what is likely to be sought by most economic development projects.

The Groundwater Withdrawal Regulations at 9VAC25-610-340 provide DEQ with the authority to deny applications for a permit for a new, expanded, or renewed withdrawal in a GWMA if “[t]he cumulative stabilized impact of the proposed withdrawal in combination with all existing lawful withdrawals will lower water levels in a **confined** aquifer below a point that represents 80% of the distance between the land surface and the top of the aquifer.” This 80% drawdown criteria is an essential regulatory criterion to prevent dewatering an aquifer, which if exceeded could lead to compaction, permanent loss of **storage**, land subsidence, and saltwater intrusion. Given the limited availability of groundwater in the VCP, the General Assembly should codify this authority to protect the Commonwealth’s groundwater resources.

Recommendation #1

The General Assembly should amend the Ground Water Management Act of 1992 to codify the existing regulatory language providing that DEQ has the authority to deny an application for a permit for a new, expanded, or renewed withdrawal in a GWMA if “[t]he cumulative stabilized impact of the proposed withdrawal in combination with all existing lawful withdrawals will lower water levels in a confined aquifer below a point that represents 80% of the distance between the land surface and the top of the aquifer.”

In certain areas of the VCP there are alternatives to groundwater, such as surface water or the potential for water reuse. Surface water or reuse water could be obtained by connecting to a water supplier. Alternatively, a self-supplied facility could obtain a Virginia Water Protection Permit to withdraw surface water or could reuse its own water to reduce or eliminate the need for a groundwater withdrawal. DEQ currently lacks clear authority to deny an application for a groundwater withdrawal permit, or to reduce the withdrawal volume in an application, on the basis that the user has alternative water sources, such as surface water or water reuse. Given the limited availability of groundwater in the VCP, the General Assembly should enact legislation to give DEQ clear authority to deny or modify an application groundwater withdrawal permit if an alternative source of water is reasonably available.

Recommendation #2

The General Assembly should amend the Ground Water Management Act of 1992 to clearly provide DEQ with the authority to deny an application for a groundwater withdrawal permit or to reduce the permitted withdrawal volume where alternative water sources, such as surface water or water reuse, are reasonably available.

4.2.2 Reconciling the Prioritization for Human Consumption with Other Provisions of the Ground Water Management Act of 1992

The Ground Water Management Act of 1992 places human consumption at the top of the groundwater use hierarchy.⁶¹ However, the Ground Water Management Act of 1992 also includes provisions to protect existing groundwater withdrawals, which can conflict with this prioritization for human consumption.⁶² For example, going back to the origins of the Ground Water Management Act of 1992, DEQ was directed to issue ground water withdrawal permits to existing users based on historic use. Provisions addressing newly created or expanded GWMA’s also require initial permits to be issued based on historic use.

In addition, groundwater withdrawal permits do not all have the same start and expiration dates, and applications for groundwater withdrawal permits are processed as they are received. When two applications from the same geographic area are received at roughly the same time it is relatively straightforward to operationalize the prioritization for human consumption if there is a conflict between the two applications,

⁶¹See VA. CODE ANN. § 62.1-263. “When proposed uses of ground water are in conflict or when available supplies of ground water are insufficient for all who desire to use them, preference shall be given to uses for human consumption, over all others.”

⁶²See VA. CODE ANN. §§ 62.1-260 and 62.1-261.

and one is clearly for human consumption. However, it is less clear how DEQ is to operationalize this prioritization when there is a new application for a withdrawal that is for human consumption that conflicts with existing previously permitted withdrawals. Often times existing users have made significant investments based on their permits, which makes it challenging to reopen an existing permit to reduce a withdrawal.

Finally, human consumption is inconsistently and narrowly defined throughout DEQ's regulations. In the Ground Water Withdrawal Regulations, "human consumption" is defined as "the use of water to support human survival and health, including drinking, bathing, showering, cooking, dishwashing, and maintaining hygiene."⁶³ As a result, there are no purely "human consumption" withdrawals. Municipal water withdrawals are typically distributed by the utility to a mix of uses including residential, commercial, and industrial customers. Data from the utilities on the classification of their customers would be needed to determine how much of the withdrawal is for human consumption.

DEQ is expected to give the highest weight to human consumption in its permitting and regulatory decisions. Unfortunately, due, in part, to the uncertainties discussed above, meeting this expectation is a difficult task. Given the lack of groundwater supply in the VCP for new and expanding uses noted above, the General Assembly should enact legislation to clarify how DEQ is to operationalize the prioritization for human consumption and to balance it against statutory directives to protect existing uses.

Recommendation #3

The General Assembly should amend the Ground Water Management Act of 1992 to clarify how the prioritization for human consumption and the goal of protecting existing uses should be reconciled and implemented through permit decisions.

4.2.3 Accounting for Lawful Unpermitted Withdrawals

Lawful unpermitted withdrawals, such as private drinking water wells, make up as much as 40% of total groundwater withdrawal volume in the eastern portion of Virginia. The number of private wells is growing as the population increases in Virginia. These withdrawals are exempt from the Ground Water Management Act of 1992 because they typically do not meet the withdrawal threshold of 300,000 gallons in any one month. As a point of reference, 300,000 gallons is approximately the amount of water used by a 30-house subdivision. Consequently, these withdrawals do not require a permit and are much more difficult to monitor or even identify.

Since 2016, certified water well systems providers (well drillers) have been required to register each private well they drill in a GWMA with DEQ within 30 days of well completion. This is a huge step toward gaining better data about these wells and their withdrawals, but many wells are still missed. First, most wells in Virginia were drilled prior to 2016, and there is no requirement for well drillers to go back and report previously drilled wells. Second, there are many wells that, for various reasons, may be drilled and not captured by this registry system.

⁶³9 VA. ADMIN CODE § 25-610-10.

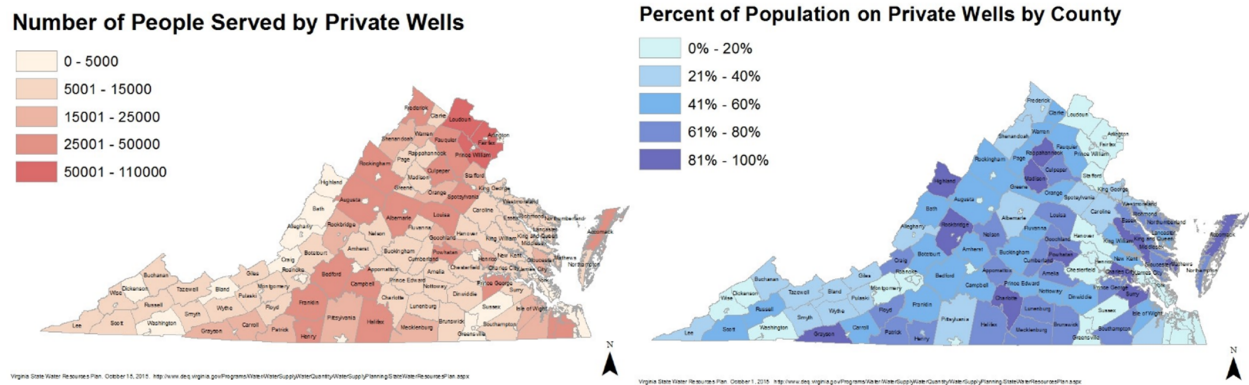


Figure 56: Maps of private well usage by county, from 2015 “Virginia State Water Resources Plan.” See also Section 1.4.3.

Locating these remaining withdrawals, which are typically residential wells, and including them in the models DEQ uses is a challenge. The information on these wells that exists is incomplete and unconsolidated. Any effort to collect what is known about them would take years and significant funding.

The Virginia Department of Health (VDH) keeps an inventory of all new private drinking water wells in Virginia. DEQ envisions creating a tool, in collaboration with VDH, to act as a groundwater withdrawal clearinghouse. This database would serve to provide VDH and DEQ and the public with up-to-date information on groundwater withdrawals in the Commonwealth. Comprehensive and reliable data on private wells would substantially improve the estimates of private domestic groundwater use. Currently, DEQ lacks both the funding and the staff to collect the necessary data. Better data and modeling would both provide DEQ with a better understanding of groundwater availability and protect existing well owners, including residential wells, since one of the elements of the technical evaluation that DEQ performs for applications for groundwater withdrawal permits examines the effect of the withdrawal on existing lawful withdrawals.

Recommendation #4

The General Assembly should appropriate \$135,000 per year in additional funding to DEQ for 1 full time equivalent (FTE) to help coordinate, analyze, and act on data regarding the aquifer system and groundwater withdrawals, including lawful unpermitted groundwater withdrawals.

As noted above, lawful unpermitted withdrawals are typically private wells serving residences. These withdrawals fall below DEQ’s permitting thresholds, and DEQ does not regulate land use decisions in the Commonwealth. However, Chapter 22, of Title 15.2 of the Code of Virginia grants localities in the Commonwealth the authority to classify and regulate development on the land in the locality.⁶⁴ In order to carry out these powers, Virginia law requires that “[e]very locality shall by resolution or ordinance create a local planning commission in order to promote the orderly development of the locality and its environs.”⁶⁵ The local planning commission “shall prepare and recommend a comprehensive plan for the physical development of the territory within its jurisdiction and every governing body shall adopt a comprehensive plan for the territory under its jurisdiction.”⁶⁶ Section 15.2-2223 of the Code of Virginia provides that a comprehensive plan “may include . . . the designation of areas for the implementation of reasonable measures to provide for the continued availability, quality, and sustainability of groundwater and surface water.” This section, however, does not require localities to consider the availability of groundwater for new planned development that has no available surface water supply or the effect of planned development on existing users of groundwater. Given the lack of future groundwater supply in the VCP noted above, the General Assembly should require

⁶⁴VA. CODE ANN. §§ 15.2-2200 *et seq.*

⁶⁵VA. CODE ANN. § 15.2-2210.

⁶⁶VA. CODE ANN. § 15.2-2223.

localities to consider groundwater availability in their comprehensive plans, particularly the availability of groundwater in areas designated for residential development that are not served by public water supplies.

Recommendation #5

The General Assembly should amend Chapter 22 of Title 15.2 of the Code of Virginia to require local comprehensive plans in groundwater management areas to limit planned growth based on groundwater availability if no other water supply is feasible.

4.2.4 Accounting for Unlawful Unpermitted Withdrawals

Unlawful unpermitted withdrawals pose many of the same challenges as the lawful unpermitted withdrawals; they can be difficult to locate and identify. Some unlawful withdrawals are made by permitted users exceeding their permit allowance. Other unlawful withdrawals are made by entities operating illegally without a permit.

Unfortunately, addressing these compliance issues requires a substantial overhaul of the currently available compliance mechanisms. DEQ is making an effort to improve inspection effectiveness, but staffing limitations make this difficult. DEQ's Office of Water Withdrawal Permitting currently employs two full-time compliance staff who share inspection and monitoring responsibility for the Virginia Water Protection (VWP) surface water withdrawal permit program and the groundwater withdrawal permitting program. This means that inspecting all 106 active VWP-permitted surface water withdrawal facilities and 378 active permitted groundwater withdrawal facilities falls on just two individuals. DEQ compliance policy requires that at least 20% of the facilities in the following categories must receive an on-site inspection every year:

1. Facilities that withdraw more than 1,000,000,000 gallons per year;
2. Facilities that withdraw between 10,000,000 and 1,000,000,000 gallons per year; and
3. Facilities that withdraw less than 10,000,000 gallons per year. Compliance staff do not currently have the capacity to meet these minimum inspection requirements.

Further, each of these individual permits may have special conditions, water withdrawal, or flowby requirements. Compliance staff must apply these unique inspection criteria to many of the facilities to ensure they comply with their permit requirements.

These same individuals are also tasked with uploading water withdrawal data received semi-and-quarter annually to DEQ's online database. Further, it falls on compliance staff to respond to complaints of potentially unlawful surface or groundwater withdrawals.

DEQ's Office of Water Withdrawal Permitting compliance staff work tirelessly to ensure permitted facilities stay within the bounds of their permits, but with only two individuals, there is currently no capacity to expand compliance and inspection activities in this program. Doing so would help DEQ stay informed on the nature of water withdrawals by permitted entities and help prevent unpermitted exceedances. However, DEQ needs funding and more staff to effectively take on these tasks.

Recommendation #6

The General Assembly should appropriate \$270,000 per year in additional funding to DEQ for 2 FTEs to enhance DEQ's groundwater withdrawal permitting compliance program.

4.2.5 Understanding Uncharacterized Areas in the VCP

As noted previously, the groundwater withdrawal permitting program relies on performing technical evaluations on proposed withdrawals, which are evaluated based on models. These technical evaluations are essential to ensure that a proposed withdrawal will not dewater an aquifer, which could lead to compaction, permanent loss of storage, land subsidence, and saltwater intrusion. The technical evaluation also ensures

that the proposed withdrawal will still be protective of existing lawful withdrawals. The quality of DEQ's technical evaluations depends on the quality of the model, which in turn depends on the data and geologic understandings that form the basis of the model. Some areas of the VCP lack data and are inadequately characterized, perhaps most notably the geologically distinct region north of Fredericksburg. DEQ's model does not currently extend into those areas. Without a serviceable model, DEQ cannot effectively perform a technical evaluation or make fully informed groundwater decisions in these areas. DEQ does not have the capacity to better characterize these areas with current staff and funding limitations.

Recommendation #7

The General Assembly should amend the Ground Water Management Act of 1992 to prohibit DEQ from issuing any permits for new significant withdrawals in portions of groundwater management areas located outside the extent of the applicable groundwater flow model.

Recommendation #8

The General Assembly should appropriate \$270,000 per year in additional funding to DEQ for 2 FTEs to improve the characterization of the VCP aquifer system, enhancing DEQ's ability to conduct technical evaluations.

4.2.6 Accounting for SWIFT

The Hampton Roads Sanitation District (HRSD) is currently developing its Sustainable Water Initiative for Tomorrow (SWIFT) program. This program, if successful, will inject potentially millions of gallons of highly treated wastewater per day into the Potomac aquifer. These injections will hopefully offset the effects from existing withdrawals from VCP system, ideally recharging it and increasing the groundwater available within the Eastern Virginia GWMA. As described above, withdrawals from industries, municipalities, and residential users have withdrawn groundwater from the Potomac aquifer faster than it can recharge naturally. The resulting drawdown has led to more restricted groundwater supply, potential for saltwater intrusion into the aquifer, and land subsidence in the overlying area.

Recharging the Potomac aquifer offers several benefits, including the conservation and protection of groundwater resources in Virginia. Other benefits include combatting land subsidence in the VCP and redirecting wastewater that would otherwise end up in Virginia's rivers and the Chesapeake Bay.

Aquifer recharge is not a novel concept. Other states have successfully implemented similar projects elsewhere in the country. However, HRSD's SWIFT project is unique in that the aquifer it will attempt to recharge, the Potomac aquifer, is far larger and deeper than those that were the subject of previous projects. The aquifer is also heterogeneous, composed of widely differing sediment types. These factors make it an exceedingly complex **hydrogeological** system. There are ongoing debates as to how water will propagate through the Potomac aquifer during full SWIFT operations. It is not entirely certain how long it will take for injections at the SWIFT sites in southeastern Virginia to affect groundwater levels in the northern reaches of the Commonwealth. Furthermore, the beneficial effects of the injections may depend on the sustained pumping into the aquifer. If injections decrease or pause, withdrawals that are offset by the injections may need to be curtailed.

As the recharge cannot yet be conclusively modeled, DEQ is not yet sure how to account for this potential recharge in its permitting decisions. Theoretically, the increased groundwater supply could allow for greater total withdrawals from the aquifer without oversubscription. However, it may be prudent to allow a period of recharge before permitting any additional withdrawals to create a groundwater supply buffer.

To better understand the as-of-yet understudied effects of the SWIFT recharge and other regional changes, DEQ recommends expanding monitoring in the VCP by adding new real-time monitoring instrumentation to existing and planned observation wells at key locations. DEQ estimates this project would require \$45,000.00 in additional funding per year of the upcoming biennium (fiscal years 2027 and 2028). Given that DEQ's existing commitments include the installation of up to 42 new observation wells in the VCP (Section 2.1.1),

this recommendation does not envision the addition of further observation wells in the near future. It may also be beneficial to study whether and where similar aquifer recharge projects could offer benefit to Virginia and its citizens.

Recommendation #9

The General Assembly should appropriate \$45,000 in additional funding per year, in each year of the biennium, to DEQ to purchase real-time monitoring equipment for observation wells to better understand changing groundwater conditions in the VCP, including the recharge effects of HRSD's SWIFT Project.

Recommendation #10

The General Assembly should appropriate \$300,000 in additional funding to DEQ to hire a contractor to study and evaluate other locations in the Commonwealth that could benefit from aquifer recharge projects similar to HRSD's SWIFT Project after the extent and magnitude of the full recharge volume is realized.

4.2.7 Groundwater Trading

Groundwater trading can take two distinct forms. Aquifer Storage and Recovery or “groundwater banking” involves injections of groundwater by an entity that withdraws the injected water, or a portion thereof, at the same place at a later time. Other variations of groundwater trading involve enabling entities to create groundwater credits, either by not using all of their permitted withdrawal or by injecting water into an aquifer, which may then be traded to another entity at a different location to enable the purchaser to withdraw groundwater at their location. Virginia laws and regulations do not currently allow for the private transfer of groundwater allocations. That is to say, if one permittee does not need or does not use the full allocation in a groundwater withdrawal permit, it cannot then transfer that unused excess to a separate entity wishing to withdraw more than its own allocation.⁶⁷

Whether to introduce such a system has been an ongoing conversation between stakeholders and Virginia regulators for many years. Stakeholders suggest that groundwater trading would lead to greater permitting efficiency or even a self-regulating market. Indeed, regulatory trading schemes exhibiting these features are not unheard of. Most notably, carbon cap-and-trade programs exist across the country and have seen relative success.

However, unlike carbon in the atmosphere, regulators cannot assume uniform and widespread mixing of groundwater. Groundwater does not flow through aquifers as if in a large tank. It takes time, as much as tens of thousands of years, for water to circulate through the VCP aquifer system. Aquifers are not simply void spaces, they are often, as in the case of the Potomac aquifer, an amalgamation of super-saturated sands, clays, and other sediments confined within impermeable geological layers. This heterogeneous composition creates an environment full of obstacles to groundwater flow, and the aquifer's depth and confining layers make it difficult to map areas of free or more-restricted flow. These challenges prevent the accurate modeling of the system, a necessary step before implementing any potential groundwater trading scheme. Without such a model, it would be hard to say with any certainty that any two given entities shared a sufficient hydrogeological connection to make them suited to trading groundwater withdrawal rights. It is also worth considering that, given the diminished capacity of the aquifer, it is advisable to reduce permit allocations to actual use upon renewal, rather than allowing entities to withdraw more than their original allocation.

Regardless of what form groundwater trading might potentially take, in addition to the scientific and technical concerns that would need to be addressed, it is necessary to consider several legal issues, including protection of the public right to groundwater resources recognized in the Ground Water Management Act

⁶⁷Such a system is typically referred to as “groundwater trading,” but it is important to note that no physical groundwater is actually transferred between parties.

of 1992.⁶⁸ This is important to ensure that new users are not required to “buy-in” through purchases from private parties to access groundwater resources and to protect lawful unpermitted withdrawals, such as private wells serving single family homes.

Any groundwater trading mechanism must also be founded on a commonly accepted allocation of rights to be traded. Virginia has no statute addressing conflicting rights to groundwater use, and therefore the common law applies. However, Virginia’s common law in this area is highly uncertain. DEQ implements other programs, such as nutrient credit trading that, in effect, create a permit right that can be traded. If groundwater withdrawals were exclusively governed by a regulatory permit, allocation of rights would be clear, but groundwater law concerns the balance between public rights and private rights to use groundwater.

Any groundwater trading mechanism would require amendments to the Ground Water Management Act of 1992 to address these legal issues. In addition, appropriations of funds would be necessary to develop the monitoring network and to analyze the data necessary to develop the scientific and technical understanding necessary to support a groundwater trading program, as well as funding to develop a trading regime and regulations.

Recommendation #11

Any legislation to amend the Ground Water Management Act of 1992 to authorize groundwater trading should first address: a) the scientific and technical consensus on the safety and reliability of groundwater trading, b) the protection of the public right to groundwater resources, c) resolution of how groundwater rights are allocated, d) whether and how to compensate parties providing the recharge of the aquifer, and e) appropriation of adequate funds to support the development of a groundwater trading regime and a budgetary plan to pay for oversight.

4.2.8 Source of Groundwater Program Funding

Many of the issues identified above are the consequence, at least in part, of a lack of funding for the solutions necessary to address them. The programs charged with implementing the Ground Water Management Act of 1992 primarily receive funding from two sources: 1) general fund allocations in the State Budget, or 2) permit fees.

DEQ’s groundwater programs are funded almost entirely by general funds. In FY 2025, groundwater withdrawal permit fee revenue totaled \$381,000. Total groundwater program expenses were around \$4 million, meaning that the program was only 9.5% funded by permit fees. Groundwater withdrawal permit fees are currently set at the statutory limit of \$9,000.⁶⁹ For context, the analogous fees for surface water withdrawal permits are subject to a \$12,000 maximum.⁷⁰

Beyond the relatively low revenue cap posed by the statutory fee maximums, permit fee revenue can be unpredictable. Permit fees, of course, are only collected when entities apply for a new or renewed permit. Recent years have seen dramatic variations in permit applications, ranging anywhere from 5 to 80 permits a year. For example, FY24 saw just \$101,000 in permit fee revenue, \$280,000 less than this most recent year. Even if DEQ could rely on 80 new or renewed permits every year, this would only generate \$720,000, far less than is needed to fund DEQ’s groundwater management activities.

Recommendation #12

In addition to increasing general fund allocations, the General Assembly should raise the statutory limit on groundwater withdrawal permit fees to an amount sufficient to initially cover at least 50% of program costs.

⁶⁸ See VA. CODE ANN. § 62.1-254 (“It is the purpose of this Act to recognize and declare that the right to reasonable control of all ground water resources within this Commonwealth belongs to the public.”).

⁶⁹ VA. CODE ANN. § 62.1-44.15:6 B3.

⁷⁰ *Id.*

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