Maryland Department of the Environment
Water and Science Administration
Water Supply Program

THE EFFECTS OF CLIMATE CHANGE ON MARYLAND'S WATER SUPPLIES

by

Patrick A. Hammond

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CONVERSION FACTORS AND SYMBOLS

Multiply	By	To obtain
Length		
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.59	square kilometer (km^2)
Volume		
gallon (gal)	3.785	liter (l)
gallon (gal)	3.785×10^{-3}	cubic meter (m^3)
Discharge Rate		
gallon per minute (gpm)	0.063	liter per second (L/s)
gallon per minute (gpm)	3.785	liter per minute (l/min)
Production Rate		
gallon per day (gpd)	3.785×10^{-3}	cubic meter per day (m^3/d)

Annual average use gallons per day gallons per day average (gpd avg)

Use during the month of maximum use gallons per day maximum (gpd max)

Transmissivity		
gallon per day per foot (gal/d-ft)	0.0124	square meter per day (m^2/d)
square foot per day (ft^2/d)	0.0929	square meter per day (m^2/d)

Use of notation: As close as possible, the original scientific or mathematical notations of any papers discussed have been retained, in case a reader wishes to review those studies.

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KEY RESULTS

The effects of the 2001-2002 drought in Maryland provides a precursor of the impacts of climate change on the water supplies in the State. In 2015, 87% of the State's public water users were supplied by surface water, primarily from the Potomac River and Washington Metropolitan Area (WMA) reservoirs, and the City of Baltimore reservoirs, supplemented by withdrawals from the Susquehanna River. Both of those major water suppliers had excess reservoir capacity remaining at the end of the record (Baltimore) or near record (WMA) drought that occurred in 2001-2002. It is likely that this excess capacity along with planned upgrades to each system would mitigate the impacts of climate change. Smaller communities supplied by surface water had to impose water restrictions during the drought due to limited storage capacity or simple intakes, and are likely to be impacted by climate change. A transition from the wet regime in the 20th and 21st centuries to a dry regime like the 8th and 9th and mid-19th centuries likely would have greater impacts on Maryland's water supplies; however, such a change is based on the uncertain results of tree ring reconstructions.

About 85% of the public groundwater use was taken from confined Coastal Plain aquifers that were unaffected by the drought. This is unlikely to change because of climate change, except for increased water demand, caused primarily by greater outdoor water due to increased evapotranspiration. Brackish water intrusion, due to pumping, has occurred in several near shore areas; however, increasing sea level rise due to climate change is unlikely to cause significantly increased intrusion at those sites. Some of the lower lying areas of Dorchester and adjacent counties may be affected by sea level rise, increasing the risk of possible brackish water intrusion and contamination of a few public water supplies withdrawing water from the unconfined portion of the Columbia aquifer along the Nanticoke River.

The remaining groundwater use was taken from the unconfined or semi-confined fractured rock aquifers of the State in central and western Maryland. Those were the public water supplies most affected by the drought due to declining well yields and are likely to be the water supplies in the State most impacted by climate change. The consensus of the scientific community is that rainfall and evapotranspiration in the State will both increase due to climate change. The scenarios included in a 2013 Interstate Commission on the Potomac River Basin (ICPRB) study were reviewed and it is expected that average groundwater runoff (effective recharge) may decline by 8% and by about 15% during a drought year. Long-term monitoring of public water supply well yields is needed to address the effects of drought and climate change. In the fractured rock areas of the State, it is estimated that about 0.5% of the domestic wells were replaced during the 2001-2002 drought. It is likely that more domestic wells may have to be replaced during a similar drought due to additional lowering of groundwater levels caused by climate change.

Introduction

During the extreme 1998–2002 drought, the major surface water suppliers in the Baltimore-Washington metropolitan area had little difficulty meeting customer demand, due to their substantial reservoir storage facilities. Many of the small to medium size towns or cities of central Maryland were required to institute voluntary or mandatory water restrictions, primarily due to declining well yields and limited reservoir storage. Lessons learned from that drought may be used to assess the potential impacts of climate change on the State's water resources.

Most of the public water in the State is supplied from the Potomac River, primarily by the Washington Suburban Sanitary Commission (WSSC), the City of Baltimore reservoirs augmented by withdrawals from the Susquehanna River, and the confined coastal plain aquifers of the southern Maryland. Although the water supplies in the fractured rock aquifers of Maryland serve a small population, it is an area likely to be most affected by climate change. A literature review was conducted to determine what studies have been completed on the potential effects of climate change on the water supplies in Maryland.

The Interstate Commission on the Potomac River Basin (ICPRB) has conducted several extensive studies on future water demand and the impacts to the Potomac River water resources due to climate change. Several academic studies have been conducted on reservoir analyses of the City of Baltimore water supply demonstrating the impacts of the 2001-2002 drought that might be useful in demonstrating the impacts of climate change on that water system.

The Maryland Geological Survey (MGS) has completed many studies on the potential yields of Maryland's coastal plain aquifers, although due to their confined features, it is expected that climate change may have little impact on those water supplies. The primary water use on the eastern shore is to supply public water from mostly confined aquifers and irrigation water from the unconfined Columbia aquifer which have also been studied by the MGS. The potential effects of sea level rise in known areas where brackish water intrusion has occurred in the coastal plain are evaluated in this investigation.

The MDE Water Supply Program has recently completed a study on the reliable drought yields of public water supplies in the fractured rock aquifers of the western Piedmont and Blue Ridge provinces of Maryland. Most of the MGS studies in this geographic area primarily relied on data from domestic wells. Available global, continental, NE USA, and Maryland studies about the effects of climate change on groundwater recharge were reviewed and used to estimate the impacts to Maryland fractured rock aquifer groundwater supplies.

Reconstructed Potomac River Flows

To demonstrate the frequency distribution of streamflow commonly involves using data collected at USGS gage sites; however, though this is the most reliable method, it covers only the last 100 +/- years. Beyond that period there are limited precipitation and temperature records for an additional 50 +/- years. For longer time frames “proxies” are used, where tree ring chronologies are the most important source of information, along with other hydrologic measures such as sediment samples, lake levels, and sea surface temperatures. These methods have been used to demonstrate climate changes over the past several thousand years. Several important long-term studies of that nature have been conducted in the Potomac River basin.

Kiang and Hagen (2004) developed a 540-year long synthetic hydrologic model to evaluate the Washington Metropolitan Area (WMA) water supply system capacity against droughts more severe than those in the existing historical record. One result indicated there were only 6 days of water supply shortages that would have required implementation of water restrictions throughout the entire 540-yr simulation, and no system failures occurred. While that data is not publicly available, Maxwell et al. (2017) reconstructed a 326-yr record of the Potomac River flows, Figure 1, indicating that 1930 was the drought of record and the 1964-1966 drought had the longest duration (years 1964, 1966 and 1965 were ranked as the 2nd, 3rd, and 4th most severe drought years). From 1838 to 1874 the low flows are less than the lowest flows of the 20th century but are below average for a much longer period.

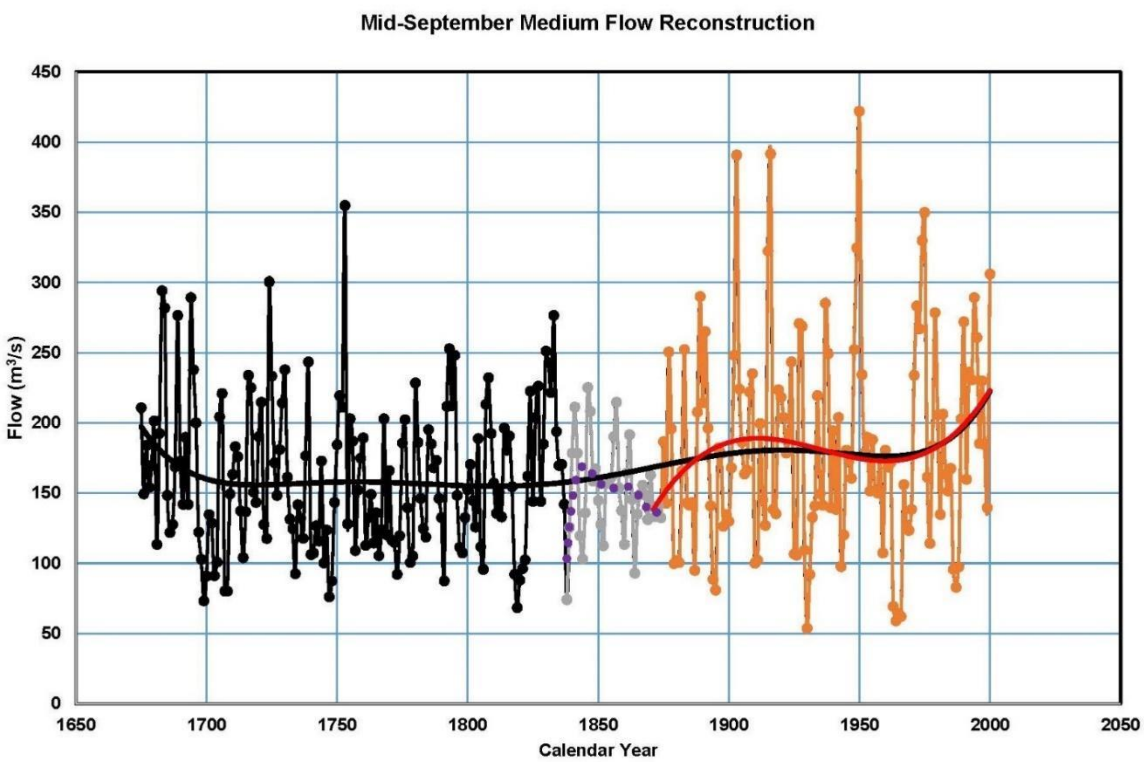


Figure 1. Potomac River streamflow reconstruction from tree ring data 1675-2000, with polynomial fits for the periods 1675-2000 (black), 1838-1874 (purple) and 1875-2000 (red). Data from Maxwell et al. (2017): http://treeflowinfo/midatl/potomac2.html. Accessed 8/26/2022.

Lorie and Hagen (2007) conducted a follow-on study using the Potomac Reservoir and River Simulation Model (PRRISM), developed by the Interstate Commission on the Potomac River Basin (ICPRB), which simulates WMA water demands, reservoir operations, and resulting river flows on a daily timestep. Since water supply withdrawals are taken upstream of Little Falls and returned to the river as wastewater treatment effluents downstream of Little Falls, the Little Falls flow data were adjusted to reflect the absence of withdrawals, with further adjustments made to remove the impact of upstream reservoir regulation. The risk of a severe drought was based on the minimum annual flow at Little Falls and the minimum annual total system reservoir storage.

Pre-instrumental streamflow was estimated using tree ring and Palmer Drought Severity Index (PDSI) reconstructions. Based on simulations of the historical flow, the synthetic data were used to generate statistical distributions of drought metrics. The drought of 1966 resulted in the lowest Potomac River flows and 55 days of deficits. The magnitude of the 1930 flows were not as great, but they lasted much longer, resulting in 121 days of deficits depleting reservoir storage at a greater rate than the drought of 1966. Consequently, it 1930 has been defined as the “drought of record” and is estimated as a 1-in-74 year event, as compared to the 1-in-327 year recurrence in the Maxwell et al. (2017) reconstruction of flows.

Water supply augmentation from WMA reservoirs was required only twice (in 1999 and 2002). At the 2025 estimated demand, simulations from the historical record indicate that there is a 20% probability of drought operations in any one year and a 30% within the larger synthetic dataset. Voluntary water restrictions are instituted when water supply storage in the Potomac River basin drops below 60% of capacity for five consecutive days, which is expected to occur 1-2% of the time in any year.

The flows at Little Falls were reconstructed using the following equation:

$$F_t = 1147.75 + 230.70\ P_t\text{, where:}$$

Where F_t = annual minimum flow at Little Falls in year t; and
P_t = average summer PDSI at node 255 in year t.

The equation was used with the reconstructed PDSI dataset to estimate the annual minimum flows at Little Falls back to the year A.D. 367, Figure 2. The all-time minimum historical flow at Little Falls minus water supply withdrawals was 350 million gallons per day (Mgd) in 1966. The reconstructed dataset falls below that minimum flow in 21 of the 1,637 years (1.28% or a 1-in-78 year event). The absolute lowest flow predicted by this reconstruction model is about 92 Mgd, which would be a catastrophic event since it does not include water supply withdrawals that would quickly deplete reservoir storage.

The 50-year moving average indicates that the 20th century was a wet period and points to longer term changes in the hydrologic regime, especially the significant multi-decadal droughts between 600 and 1050. Tree ring and lake sediment records indicate that some of the most severe and prolonged droughts to impact North America–Mesoamerica occurred between AD 650 and 1000, particularly during the 8th and 9th centuries, which coincides with the collapse of the Mayan civilization during the Terminal Classic Period (AD 750-950), Acuna-Soto et al. (2005).

The results from the PDSI reconstruction suggest that there have been extended periods of time during which conditions were much dryer than anything experienced in the last 100 years. Although the data has a high degree of uncertainty, it suggests that the Potomac River basin has been in a wet hydrologic period for the past several decades. Lorie and Hagen (2007) indicated that the risk of an extreme drought was low in 2007 and was expected to continue for another 20 of 30 years. They also suggested that the transition from a long-term wet to dry regime may occur over a few decades, providing sufficient time to plan for the next extreme drought in the Potomac River basin.

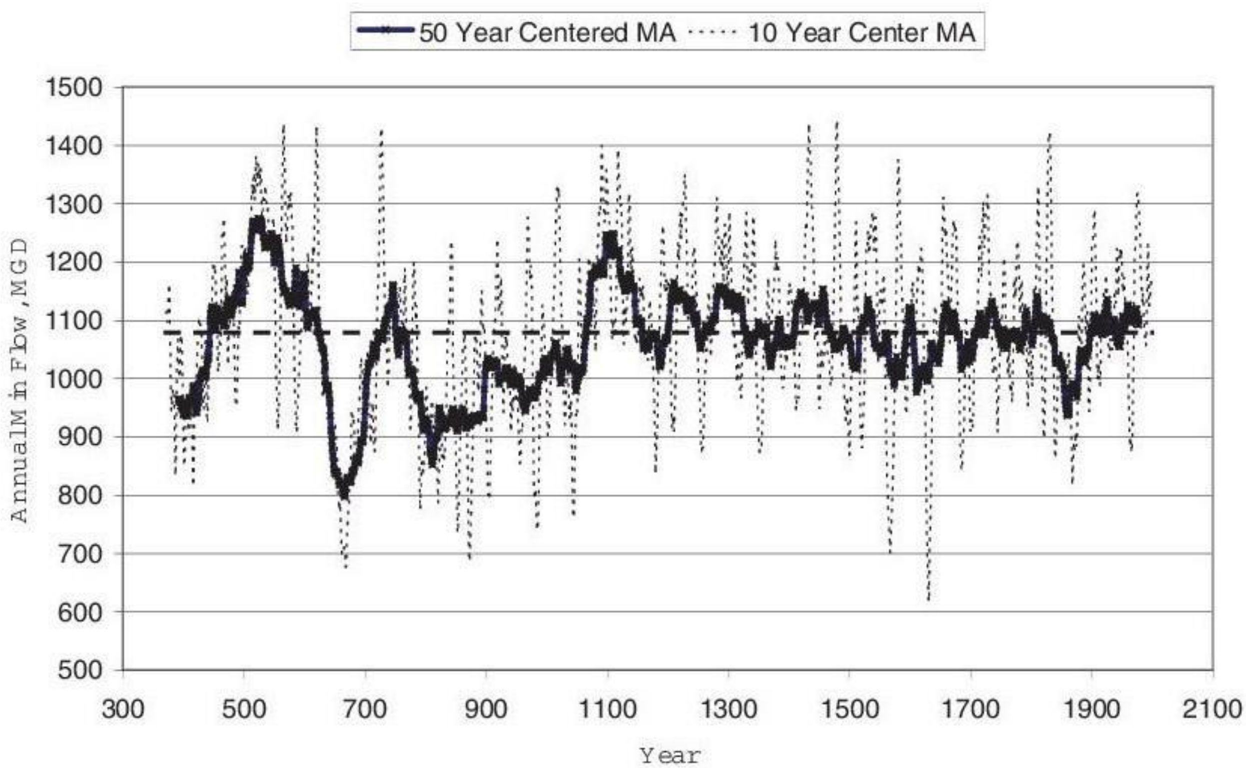


Figure 2. 10-yr and 50-yr moving averages of Potomac River PDSI stream flow reconstruction 367-2004. Reproduced from Lorie and Hagen (2007), Fig. 8.

Climate Change Impacts on Washington Metropolitan Area Potomac River Water Supplies

Ahmed et al. (2020) completed a study on the Washington Metropolitan Area (WMA) water supply that forecasts the demand and resource availability for the Year 2050. It is the most recent in a series of seven reports published every five years starting in 1990 and considered the potential impact of climate change on system water resources.

The WMA includes the District of Columbia and the portions of the Maryland and Virginia suburbs that are supplied water, either directly or indirectly, by Fairfax Water, the Washington Aqueduct, Washington Suburban Sanitary Commission (WSSC) Water (CO-OP suppliers), Loudoun Water and the City of Rockville. The Potomac River supplies, on average, just over three quarters of the WMA's water and is augmented during droughts from three upstream reservoirs: Jennings Randolph, Little Seneca, and Savage. The remaining one quarter of the water is supplied from reservoirs on the Occoquan River and the Patuxent River. Future planned resources are Loudoun Water's Milestone Reservoir, scheduled for completion in 2024, and Fairfax Water's Vulcan Quarry Phase 1, to be completed in 2040.

The study satisfies requirements of the Low Flow Allocation Agreement (LFAA), signed in 1978 by the United States, the State of Maryland, the Commonwealth of Virginia, the District of Columbia, WSSC Water, and Fairfax Water; and the Water Supply Coordination Agreement (WSCA), signed in 1982 by the United States, Fairfax Water, WSSC Water, the District of Columbia, and ICPRB. These agreements were largely initiated because of water supply problems that occurred during the mid-1960's drought. The United States Army Corps of Engineers (USACE) previously had identified 16 potential dam sites on the Potomac River upstream of the District of Columbia, whose reservoirs could augment supply during low-flow periods, USACE (1963); however, public opposition led to the construction of only the Jennings Randolph Reservoir

The LFAA defines how Potomac River water withdrawals will be allocated between the suppliers if the total flow cannot meet the needs of each supplier plus an environmental flow-by at Little Falls dam of 100 Mgd, which is equal to 20% of the 7Q10 (498 Mgd), Cummins et al. (2010). The WSCA provides for the coordinated use of the major water supply facilities in the region, including those on the Patuxent and Occoquan rivers, as a means of minimizing the potential of triggering the LFAA's low-flow allocation mechanism. Operating rules specify that the free-flowing Potomac River is used during winter and spring months of low-flow years to preserve storage in the Patuxent and Occoquan reservoirs. Since 1982, water supply releases to augment the natural flow of the Potomac River for water supply purposes have been made from the Jennings Randolph and Little Seneca reservoirs during low-flow periods in the summers of 1999 and 2002, and in the fall of 2010, with the augmented flows providing the required amount of water.

Reservoir releases of 6.1 billion gallons (Bgal) used to augment Potomac flow in 2002 lowered the water supply storage in Jennings Randolph and Little Seneca Reservoirs to a minimum of 11.1 Bgal (65% full) on September 22, 2002, Figure 3, Kiang and Hagen (2003). Also shown is a comparison of the 2002 reservoir storage with modeled storage under hydrological conditions that occurred during the 1930 historical drought of record. The figure shows that the drought of 1930 would have caused reservoir storage to drop to about 50% full and it would have taken much longer to refill than in 2002. The model demonstrates that the WMA water supply could have survived a record drought with remaining storage that would be available during a more severe drought as the result of climate change.

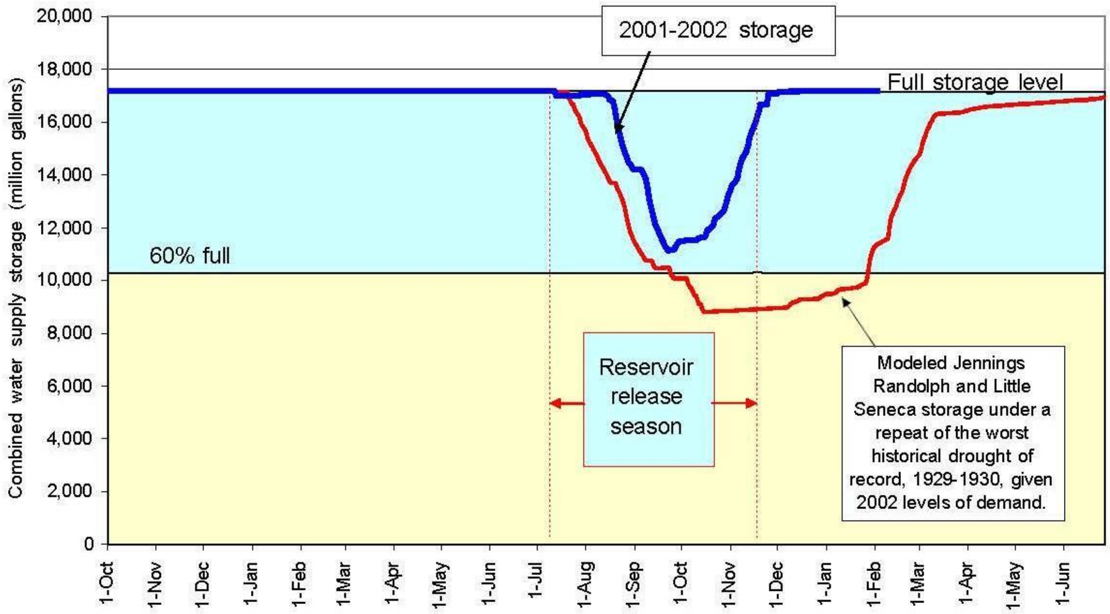


Figure 3. Water supply storage at Jennings Randolph and Little Seneca Reservoirs, 2002. Combined storage reached a minimum of 11.1 Bgal (65% full) on September 22, 2002. Reproduced from Kiang and Hagen (2003), Fig. 2-5.

Previous projections of water use in the WMA have been substantially in error, Figure 4, as water use has remained steady for almost three decades despite continuing population growth, Ahmed et al. (2020). The WMA population rose 41% over that period to 4.8 million people, while water demands had essentially remained constant caused by falling per household and per employee use due to increased efficiencies of household and commercial water fixtures and appliances. The population forecast for the WMA is 6.1 million in 2050, a 27% increase from 2018. During the period, 2014-2018, total production by the three CO-OP suppliers averaged 453 million gallons per day (Mgd), with 137 Mgd for Washington Aqueduct (30% of system total), 153 Mgd for Fairfax Water (34% of system total), and 163 Mgd for WSSC Water (36% of system total). Average annual demand in the WMA, including Rockville, is projected to increase to 528 Mgd (16%) by 2050, with an estimated uncertainty of ±10.4%.

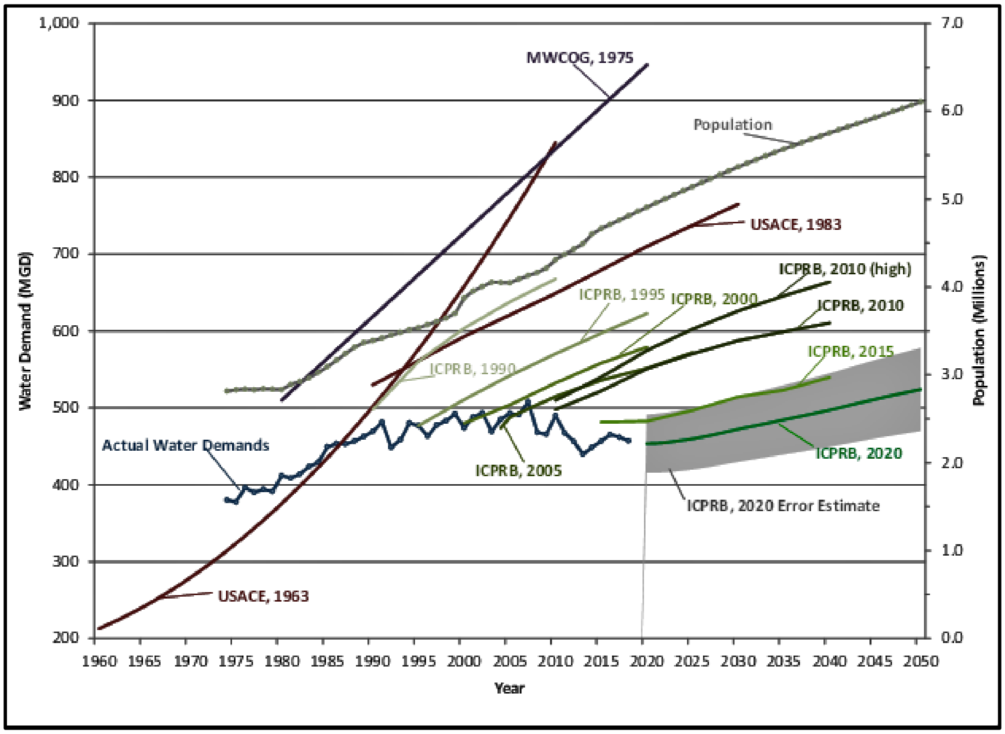


Figure 4. Current and past forecasts of WMA water demand (excluding Rockville). Reproduced from Ahmed et al. (2020), Fig. ES-3.

Potential Impacts of Climate Change

In the Ahmed et al. (2020) study, 1896 through 1979 was assumed to be a period unaffected by climate change within the Potomac River basin. Projections indicated that the mid-Atlantic states, on average, were becoming and would continue to get “wetter”, while temperatures are expected to rise. To show the potential impacts of climate change on the WMA water supply, ICPRB uses the Potomac Reservoir and River Simulation Model (PRRISM), a complex flow mass technique used to determine the yield of the multi-reservoir water supply system. The results of the simulations in the 2020 study are reproduced in Table 1.-The climate change analysis is based on 224 climate change projections of precipitation and temperature from global climate models (GCMs) that were adjusted, via a technique called bias correction and spatial disaggregation (BCSD), to improve the match with the historical record in the Potomac basin. Nine scenarios for future conditions were produced by combinations of three demand and three flow scenarios, based on the study’s forecasts for total WMA demand and Potomac River flows, plus or minus the estimated standard errors.

The three demand scenarios are:
Low Demands: total WMA demand is 453 Mgd in 2040 and 474 Mgd in 2050,
Medium Demands: total WMA demand is 501 Mgd in 2040 and 528 Mgd in 2050,
High Demands: total WMA demand is 550 Mgd in 2040 and 583 Mgd in 2050

The descriptions in Table 1 give results for representative annual flows in "very wet", "average", and "very dry" year scenarios

Table 1. Response of Potomac Basin streamflows to rising temperatures in 2040 and 2050. Reproduced from Ahmed (2020), p. ES-5.

HOW WILL POTOMAC BASIN STREAMFLOWS RESPOND TO RISING TEMPERATURES IN 2040 AND 2050?

***Lower Flows Scenario – significant response*:**

- 11% to 14% increase in very wet years
- Little change in average years
- 27% to 35% decrease in very dry years

Medium Flows Scenario – moderate response:

- 14% to 18% increase in very wet years
- 5% to 6% increase in average years
- 9% to 13% decrease in very dry years

Higher Flows Scenario – minimal response:

- 18% to 23% increase in very wet years
- 11% to 13% increase in average years
- 7% to 8% increase in very dry years

When state drought management measures are simulated, the results indicate that the average Potomac River flow from June through September increases by 6 to 12 Mgd, and the minimum flow above WMA intakes improves by 10 to 18 Mgd during a severe drought.

PRRISM was then used to assess the performance of the WMA water supply system under all nine future conditions scenarios for four potential future system configurations, shown in Table 2, in response to forecasted water demands influenced by future climate change.

Table 2. Potential changes to WMA water supply System, Reproduced from Ahmed et al. (2020), p. ES-6.

WHAT WILL THE FUTURE WMA WATER SUPPLY SYSTEM LOOK LIKE?

Baseline: Current resources + Milestone Reservoir + Vulcan Quarry, Phase 1.

Baseline + Ops: Baseline + four recommended operational alternatives

Baseline + Ops + Travilah: Baseline + Ops + Travilah Quarry

Baseline + Ops + Travilah + Luck: Baseline + Ops + Travilah + Luck Stone Quarry B

. The results of the PRRISM analyses are given below in Table 3 (2040) and Table 4 (2050), where the colors indicate system performance during a severe drought, comparable to the 1930 drought of record but in an altered climate. The system is considered reliable if the percent years with no Potomac River flow deficits are greater than or equal to 99.88%, and the percent years with emergency water use restrictions is less than or equal to 0.06%.

The following colors indicate the reliability of the system performance:

GREEN – denotes reliable performance,

YELLOW – denotes marginal performance, if one or both of the reliability criteria are not met but the maximum Potomac deficit on a single day is very small (averaging 1 Mgd or less), and

RED – denotes system failure, that is, an inability of the system to meet combined WMA water supply and environmental flows in the event of severe drought

Table 3: WMA water supply system performance for 2040.
Reproduced from Ahmed et al. (2020), Table ES-1.

	Higher Flows			Medium Flows			Lower Flows		
	Low Demands	Medium Demands	High Demands	Low Demands	Medium Demands	High Demands	Low Demands	Medium Demands	High Demands
Baseline	Green	Green	Green	Green	Yellow	Red	Red	Red	Red
Baseline + Ops	Green	Green	Green	Green	Green	Yellow	Red	Red	Red
Baseline + Ops + Travilah	Green	Green	Green	Green	Green	Green	Green	Green	Yellow
Baseline + Ops + Travilah + Luck	Green	Green	Green	Green	Green	Green	Green	Green	Green

.

Table 4: WMA water supply system performance for 2050 scenarios.
Reproduced from Ahmed et al. (2020), Table ES-2.

	Higher Flows			Medium Flows			Lower Flows		
	Low Demands	Medium Demands	High Demands	Low Demands	Medium Demands	High Demands	Low Demands	Medium Demands	High Demands
Baseline	Green	Green	Yellow	Yellow	Red	Red	Red	Red	Red
Baseline + Ops	Green	Green	Green	Green	Yellow	Red	Red	Red	Red
Baseline + Ops + Travilah	Green	Green	Green	Green	Green	Green	Yellow	Red	Red
Baseline + Ops + Travilah + Luck	Green	Green	Green	Green	Green	Green	Green	Red	Red

The proposed operational alternatives are cooperative operations of the Milestone Reservoir, the Beaverdam Reservoir used for low-flow augmentation, improved river flow forecasts, and the use of Jennings Randolph water quality storage, Schultz et al (2017). Though the benefit to the WMA system of any one of the operational alternatives was modest, the combination of all four was significant in terms of the increase of the system safe summer yield, to about 25 to 80 Mgd, depending on the climate change scenario. Ahmed et al. (2020) estimated that the total existing capacity of the reservoirs would decline by 9.2% by 2050 because of sedimentation. The water availability forecasts included this loss in reservoir storage capacity.

The projected long-term mean precipitation in Table 5, steadily rises over the 150-year simulation period of the BCSD projections, from 38.8 in/yr for the base period, 1950-1979, to 42.9 in/yr for 2040-2069 and 43.7 in/yr for 2070-2099, or increases of 10.6% and 12.7%, respectively. Also, long-term mean temperatures increase from 51.7 °F in the base period to 56.4 °F and 57.9 °F for the future periods of 2040-2069 and 2070-2099 or increases of 4.7 °F (+9.1%) and 6.3 °F (+12.2%), respectively. The standard errors for the two future periods; however, are 38% and 44%.

Table 5. Annual precipitation and temperature for the Potomac basin – long-term means and standard deviations from BCSD filtered projections. Reproduced from Ahmed et al. (2020), Table 6-2.

	Precipitation			Temperature		
Time interval	**Mean, mm/year (inches/year)**	**Change in mean from study base period, percent**	**Standard deviation, mm/year (inches/year)**	**Mean, °C (°F)**	**Change in mean from study base period, °C (°F)**	**Standard deviation, °C (°F)**
From historical data (PRISM)						
1896-1979	991 (39.0)	0.6	128 (5.0)	11.19 (52.1)	0.3	0.60 (1.1)
From ensemble of 224 BCSD filtered projections						
1950-1979 (study base period)	985 (38.8)	0.0	138 (5.4)	10.94 (51.7)	0.0 (0.0)	0.60 (1.1)
1980-2009	1011 (39.8)	2.6	145 (5.7)	11.45 (52.6)	0.5 (0.9)	0.67 (1.2)
2010-2039	1052 (41.4)	6.8	154 (6.1)	12.55 (54.6)	1.6 (2.9)	0.76 (1.4)
2040-2069	1089 (42.9)	10.6	164 (6.5)	13.57 (56.4)	2.6 (4.7)	0.99 (1.8)
2070-2099	1110 (43.7)	12.7	169 (6.7)	14.41 (57.9)	3.5 (6.2)	1.49 (2.7)

There is a wide range in the projected change in flows during an approximate 100-yr drought. For the respective Very Dry, Dry, and Medium groups of runs, the future flows may be 36%, 16%, or 12% lower than historic flows. Changes in the temperature coefficient, ß2, had a significant effect on the low-flow values, where changes in annual flows in extreme drought years may range from -40% to +7%. In the 2050 simulation: change in daily flows during the drought of record (1930) was -38%, -14%, and +8% for the Lower Flows, Medium Flows, and Higher Flows scenarios, respectively**.**

Climate change has little effect on average annual WMA demands, which only increase to about 6 Mgd (1%) in 2050. But the projected rise in temperature does have a greater impact on summertime demands in that the peak mean July demand is predicted to rise by25 Mgd (4%) in 2050. A 10% reduction in upstream consumptive use (9.6 Mgd in 2040) could improve the WMA system safe summer yield by 15 Mgd. Maryland and Virginia maintain drought response plans that could also reduce peak summertime demand. In Maryland the four drought level stages are Normal, Watch, Warning and Emergency. Figure 5 (Western Region) and Figure 6 (Central Region) indicate which years and the number of occurrences when the different stages were instituted.

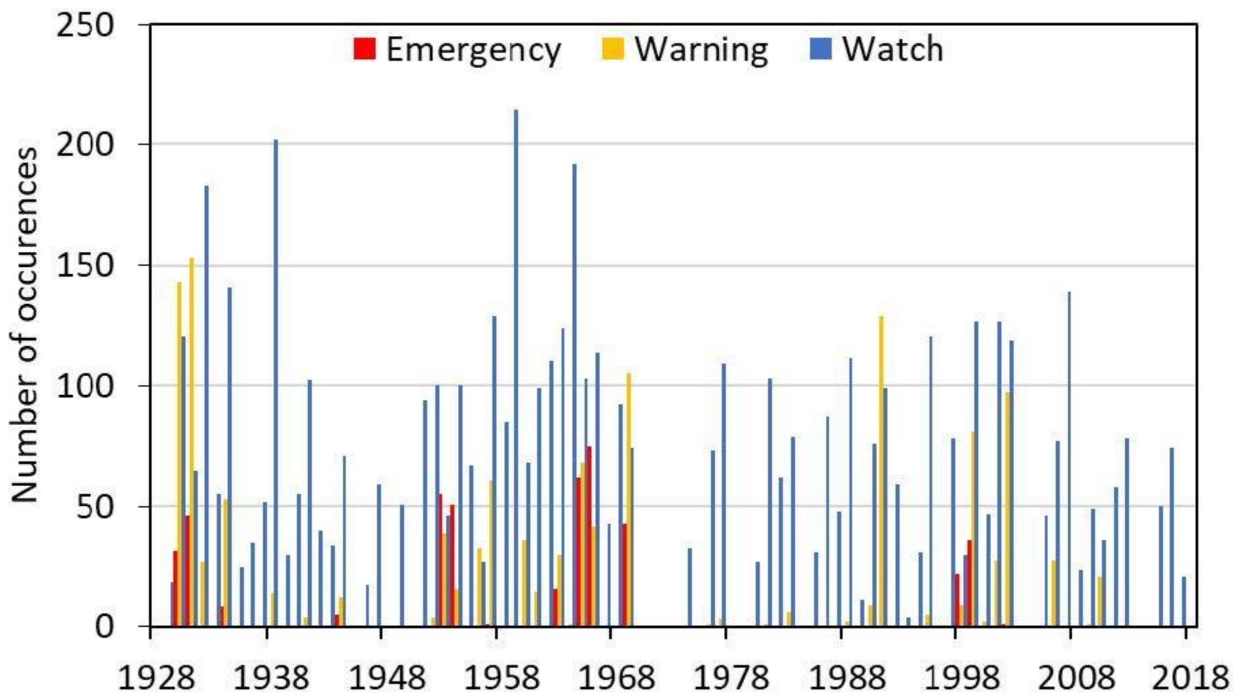


Figure 5. Drought time series summary in Maryland Western Region. Reproduced from Ahmed et al. (2020), Fig. 7-4.

The Ahmed et al. (2020) study assumed that a drought watch stage would not lead to significant reduction in upstream water use, while a drought warning stage could reduce water use by 5% to 10%, and a drought emergency stage, with mandatory water restrictions, could reduce water use by 10% to 15% With state drought management measures in place the 1930 PRRISM simulation indicated that the average summertime (July-September) Potomac River flow increased by 6 to 12 Mgd and the minimum flow above WMA intakes improved by 10 to 18 Mgd.

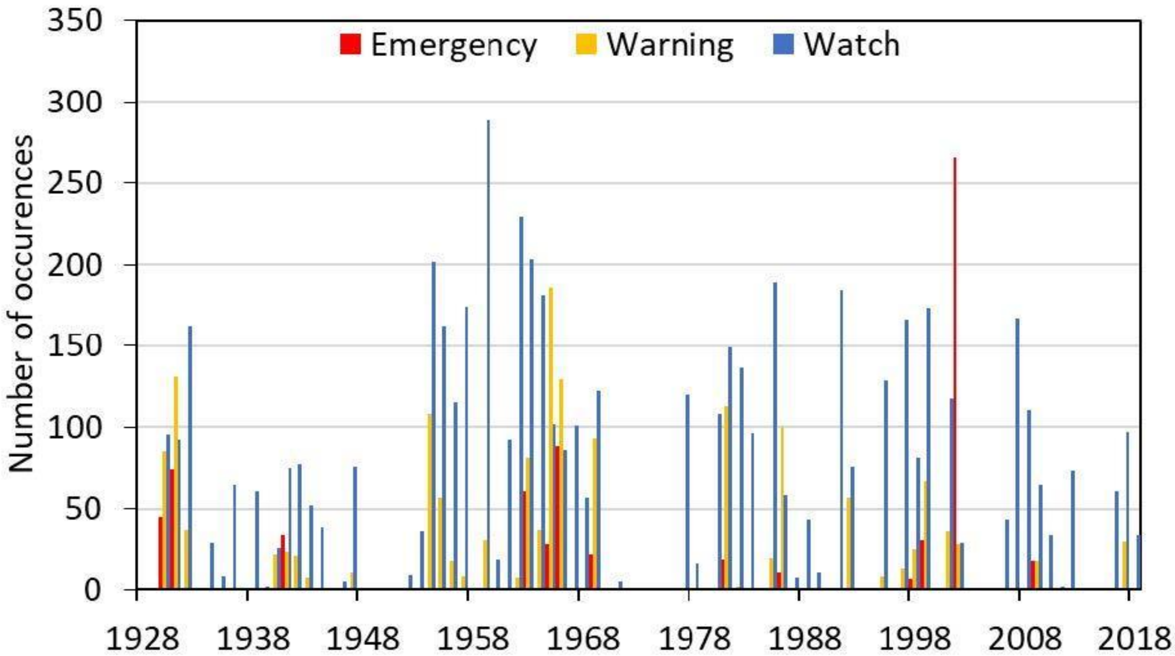


Figure 6. Drought time series summary in Maryland Central Region Reproduced from Ahmed et al. (2020), Fig. 7-3.

Conclusion

The 2050 PRRISM simulations for the WMA Baseline system, consisting of current resources plus the addition of Loudoun Water's Milestone Reservoir and Fairfax Water's Vulcan Quarry, Phase 1 performs well in a severe drought, under two of the Higher Flows scenarios, but experiences difficulties, ranging from moderate to extreme, under all other scenarios The implementation of the four operational alternatives improves system performance significantly under the Medium Flows/Medium Demands scenario and two other scenarios. With the addition of the Travilah Quarry, the system performance becomes reliable or marginal under three additional scenarios. However, even with both the Travilah and Luck quarries in place, PRRISM simulations indicate that during a severe drought, the system is unable to meet WMA water demands plus the Little Fall flow-by under two of the Lower Flows scenarios. If there is no climate change, the system performance is marginal in 2050; however, with the addition of the four operational alternatives system performance would then be rated as reliable.

Ahmed et al. (2020) indicated that no single scenario in the study was more or less likely to represent future water supply availability than any other. It was recommended that more information is needed to determine the likelihood of the 2050 Lower Flows climate scenario. ICPRB's next planned water supply study in 2025, and each succeeding 5-yr report, will reassess the potential impact of climate change on regional streamflow based on additional data on climate and flow trends and projections.

City of Baltimore Water Supply System: Planning for Potential Drought

Baltimore's water supply system is managed by the Water and Wastewater Bureau of the City of Baltimore Department of Public Works (DPW). Three major surface supply reservoirs serve Baltimore: Patapsco River watershed, Prettyboy Reservoir (with a drainage area of 80 mi^2 and a storage of 19 billion gallons or Bgal) and Loch Raven Reservoir (with a drainage area of 223 mi^2 and a storage of 23 Bgal), and Gunpowder River watershed, Liberty Reservoir (with a drainage area of 163 mi^2 and an active storage of 43 Bgal). In total, the contributing watersheds cover an area of approximately 467 mi^2. The system has 85 Bgal of total storage, with 15% reserved for water quality, for a total available storage of 72 Bgal. The three reservoirs serve as the main source of water supply to 2 million consumers within the city limits and in surrounding counties, using at present an estimated 225 Mgd avg. McIntyre (2016)

The City of Baltimore also maintains a pipeline from the Susquehanna River at Conowingo Pond for use during drought emergencies. The supplemental supply is taken at the Deer Creek Pumping station from the Susquehanna River north of Aberdeen and travels 38 miles to the Montebello Filtration Plants. The City extracts water only when necessary due to the costs associated with pumping and treatment, as well as fees paid to the Exelon Corporation. Water treatment costs for Baltimore can be managed by using smaller proportions of the typically lower quality Susquehanna water as drought conditions improve.

The August 9, 2001, settlement agreement between the City of Baltimore and Susquehanna River Basin Commission (SRBC) allows the City to withdraw and divert up to 250 Mgd, although the best information available at that time indicated that the Deer Creek pumping station was only rated at 137 Mgd. As of 2014, an additional pump was being installed that would bring the pumping capacity up to approximately 190 Mgd. Under low flow conditions, the withdrawal is limited to 84 Mgd on a 30-day average and a maximum daily use of 142 Mgd, based on the low flow triggers at the USGS Susquehanna River Marietta stream gage contained in Table 6. Added to the table are the average monthly during the time periods in 2002. There was a 46-day period from 08/08/2002 to 09/23/2002 when flows were less than the Q_{FERC}[1] trigger values, when withdrawals would have been limited to a 30-day average of 84 Mgd and a one-day maximum of 146 Mgd.

Table 6. Q_{FERC} triggers for low flow events at the Marietta, PA USGS streamflow gage. Data from SRBC Docket No. 20010801 and USGS stream gage 01576000, Susquehanna River at Marietta.

Time Period	Q_{FERC}	Qflow 2002
April 1 – April 30	10,000 cfs	45,200 cfs
May 1 – May 30	7,500 cfs	79,500 cfs
June 1 – September 15	5,000 cfs	4,190-46,500 cfs
September 16 – November 30	3,500 cfs	4,190-39,800 cfs
December 1 – February 28/29	1,600 cfs	46,600 cfs
March 1 – March 31	3,500 cfs	41,940 cfs

[1] Federal Energy Regulatory Commission (FERC)

During the drought of 2001-2002, the water diverted from the Susquehanna River by the City of Baltimore was needed to supply demand due to declining reservoir levels. An analysis of the nearby streamflow data collected at the USGS Deer Creek at Rocks stream gaging station indicated that 2002 was the drought of record (for the period 1929-2021), with baseflow (BF) equal to 5.7 in/yr and total streamflow (SF) of 7.5 in/yr, as compared to 1931 (BF=5.9 in/yr, SF=8.6 in/yr), 1966 (BF=6.5 in/yr, SF=8.9 in/yr) and 1981 (BF=6.7 in/yr, SF=8.4 in/yr). As a result of the earlier 1998-1999 drought the State of Maryland adopted the Drought Monitoring and Response Plan, which includes tracking the levels in major water supply reservoirs, including those of the City of Baltimore. In the case of 2002, water levels are available for November and December 2001, and January through March, May, August, and September 2002, Table 7. While the actual water used by the City was not available, it was estimated by using the average of the previous three years for similar time periods. The total amounts are like the 273 Mgd for water use reported in the Baltimore City Source Water Assessment Plan for the Liberty Reservoir. Water restrictions were imposed on August 27, 2002, and lifted March 20, 2003. Although the drought was essentially over at the end of September, restrictions were needed until the storage in the reservoirs had recovered substantially. Without the withdrawal and diversion from the Susquehanna River, and including the 15% reserve, there would have been a deficit of 3.6 Bgal or about 5% of the reservoir capacity. Without the reserve, the remaining storage would have been 9.2 Bgal.

Table 7. City of Baltimore reservoir storage capacities and water use during 2001-2002 drought, with withdrawals from the Susquehanna River.

Year	Month	Liberty					Loch Raven			Prettyboy			Loch Raven/Prettyboy			Susquehanna River	
		Storage (Bgal)	% Full	Remaining (Bgd)	Days Storage	Use (Mgd)	Storage (Bgal)	% Full	Remaining (Bgd)	Storage (Bgal)	% Full	Remaining (Bgd)	Remaining (Bgd)	Days Storage	Use (Mgd)	Use (Mgd)	Use (Mgal)
2001	Nov	43	78	33.5	309	108.4	23	78	17.9	19	35	6.7	24.6	130	189.2	0	0
2001	Dec	43	70	30.1	280	107.5	23	71	16.3	19	35	6.7	23	121	190.1	0	0
2002	Jan	43	66	28.4	258	110.1	23	70	16.1	19	30	5.7	22.4	118	189.8	3.3	103.10
2002	Feb	43	62	26.7	268	99.6	23	70	16.1	19	31	5.9	22	113	194.7	90.4	2,532.00
2002	Mar	43	61	26.2	252	104	23	77	17.7	19	34	6.5	24.2	127	190.6	108.9	3,375.50
2002	May	43	61	26.2	247	106.1	23	77	17.7	19	34	6.5	24.2	125	193.6	102.9	7,087.50
2002	Aug	43	44	18.9	213	88.7	23	73	16.8	19	25	4.8	21.6	113	191.2	79.7	10,573.10
2002	Sep	43	36	15.5	176	88.1	23	75	17.3	19	17	3.2	20.1	105	191.8	72.9	2,188.20
																Total	25,859.40

Water taken from the Liberty Reservoir is treated at the Ashburton WTP

Water taken from the Loch Ravne and Prettyboy Reservoirs is treated at the Montebello WTPs

Total storage remaining Sept 30, 2002 = 35.1 Bgal / Water withdrawn susquehanna River = 25.9 Bgal Jan-Sep 2002

15% of storage (12.8 Bgal) is presently reserved for sediment in-fill.

Remaining storage without Susquehanna River withdrawals and 15% reserve = -3.6 Bgal

McIntyre (2016) conducted a study that developed and analyzed a drought plan for the City of Baltimore, in the context of system performance, with a set of operating policies that incorporate streamflow forecasts. The Days of Supply Remaining (DSR) index was recommended as it balances high storage levels with low water restrictions and pumping frequency. The following three forecasting models were used in the study: 1) Global Ensemble Forecast System (GEFS), 2) Climate Forecast System version 2(CFSv2), and 3) Ensemble Streamflow Prediction (ESP). Each forecast was assessed at twelve different forecast intervals—from one to twelve weeks.

The Drought Action Response Tool (DART) is a water supply systems model that incorporates different operating policies and testing of the effects of forecasts system performance. DART simulates: 1) reservoir storage, streamflows, and operating policies, and 2) evaluates drought plans suggested by both the DPW and the SRBC, including auxiliary pumping from the Susquehanna and mandatory or voluntary water restrictions in response to droughts, Booras (2016).

If the DSR value drops below the seasonal 25%, 12% or 5% trigger threshold on any day, the system enters a specific drought level and category. Drought Plan Levels/Categories according to Percentile Thresholds Trigger, Threshold Drought Level, and Drought Category are: 25th Percentile, Level 1, Watch; 12th Percentile, Level 2, Warning; and 5th Percentile, Level 3, Emergency.

The goal of the Booras (2016) study was to identify a robust operating plan that makes use of the National Oceanic and Atmospheric Administration/Mid-Atlantic River Forecast Center (NOAA/MARFC) forecasts and ensures adequate system performance for the City of Baltimore at a reasonable cost. A set of 24 operating rules exploring the City of Baltimore's operations and withdrawals from the Susquehanna River were designed to evaluate overall system management alternatives.

The City of Baltimore DPW and the SRBC proposed an extensive set of operating policies to be tested by DART. The policies were classified in seven categories—each of which explores different options for the timing and level of pumping from the Susquehanna River. Only four of those scenarios provided potential optimum performance by either using incremental pumping (starting with a low pumping rate at drought level one and then at higher rates as the drought level increases) or pumping at various rates when the total reservoir storage level dropped below 75% of capacity. The first policy group, entitled "Standard Pumping", reflected current system operations. Pumping rates of 50, 80, 137 and 190 Mgd simulated turning on one to four pumps at the Deer Creek Pumping Station. "Summer Pumping" was defined as only pumping from the Susquehanna River during the summer months (June through September) at the rates indicated above and not including the DSR trigger levels. This maintained a high surface water reservoir quality during a time in which water quality is typically low but did not consider the current system storage, allowing for pumping from the Susquehanna River in the summer when the reservoirs may be full and spilling. The "Summer Refill" policy is designed to ensure that the reservoirs are full by or through certain summer months (May, June, or July). Each of these five scenarios required pumping at a rate of 137 Mgd to maintain a full reservoir. The "Proactive Pumping" policy was initiated using the Susquehanna River water only during drought level 2 as a pre-emptive action, then switches back to the surface water reservoirs for supply during periods of low stream flow.

The results showed that the water managers should use the scaled GEFS forecasts at outlooks for no greater than four weeks, and then switch to the AR-1 forecasts at outlooks greater than four weeks. The model and drought plans created in that study should be updated as streamflow forecasting technology improves.

A flow mass analysis was performed by Booras (2016), Figures 7 and 8, that evaluated the MARFC forecasts in comparison to a baseline forecast and a "perfect" forecast. The baseline forecast is calculated using average monthly values to estimate future inflows. The perfect forecast uses the observed streamflows in place of a forecast. Each forecast scenario met the target minimum storage threshold of 40% and triggered the same frequency of auxiliary pumping (9%). Mandatory curtailments occurred more frequently with MARFC forecasts than the perfect and baseline forecasts. The baseline forecast scenario had the most severe drop in minimum storage.

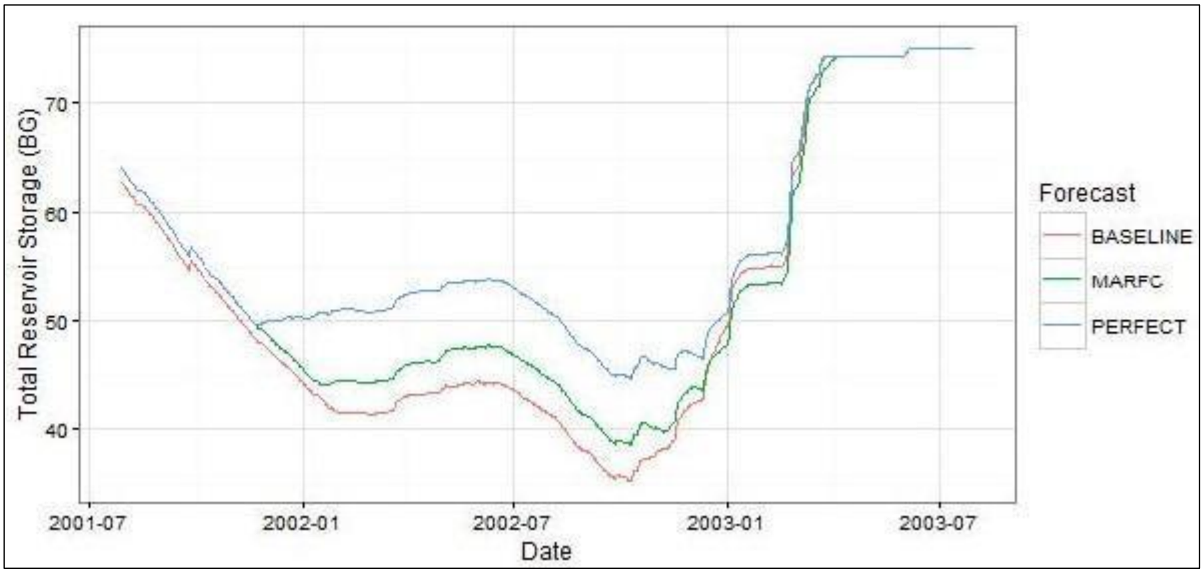


Figure 7. Total City of Baltimore reservoir storage DART simulation results during 2002 drought, MARFC forecast value assessment, Reproduced from Booras (2016), Fig. 16.

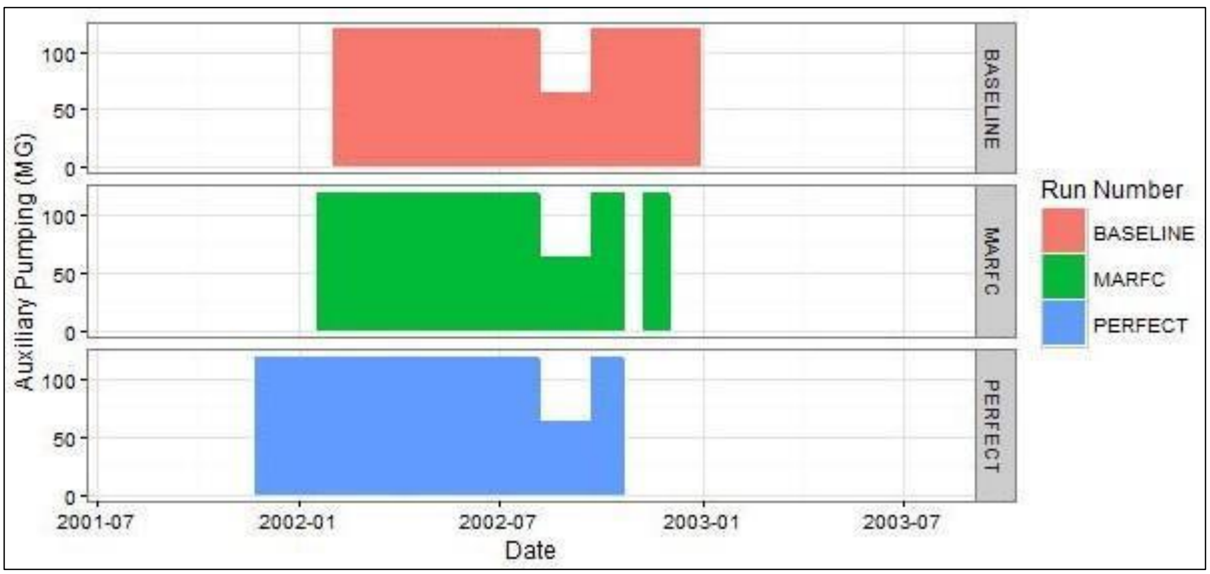


Figure 8. City of Baltimore auxiliary pumping DART simulation results during 2002 drought, MARFC forecast value assessment. Reproduced from Booras (2016), Fig. 17.

A second analysis was performed to evaluate the three forecast incorporation methods (DSR, Binned and Median). Unlike the first analysis, the three methods differed in the frequency with which drought mitigations were called for and how effective those actions were. High reservoir storages were achieved only by neglecting the costs associated with pumping and curtailments. Overall, the DSR metric more closely met the desired performance metrics, likely due to the inclusion of system status and demand in the calculation.

A third analysis was performed to determine which aggregate drought index best increased performance for the water supply system. An aggregate drought index is used to time drought management actions. Fifty-one DART simulations were run, with combinations of traditional indicators and MARFC streamflow forecasts. DSR achieved the best balance of using curtailments and pumping efficiently to meet the total desired storages by timing the drought mitigation actions well.

Climate Change and Water Demand Sensitivity

The impacts of climate change on the water system were simulated using a projected range of 10% to 50% reduction in summer streamflow. This was based on published expected precipitation changes in the Mid-Atlantic region of between -4 to +27%, Najjar et al. (2000), with -5 to -10% during summer months, Ning et al. (2012). The higher reduction in summertime flows was associated with increased temperatures and evapotranspiration. The analysis focused only on summer streamflow volumes because those were the flows that may decrease, while total annual precipitation values were expected to increase. Future water demand was varied from a 50% reduction to a 50% increase, to determine the point at which the system would fail to meet water demand.

The largest vulnerabilities caused in the system are from changes in water demand and not changes in summer streamflow values. There was only a slight decrease in minimum total storage even over large decreases in streamflow (50% reduction). However, high increases in demand led to a sharp decline in performance, especially at a 50% increase. Even considering increased outdoor water use due to climate change, this was an unrealistic result since the population supplied by the water system is only projected to increase by 9.7% by the year 2040. Technological innovations and water conservation improvements could mitigate the effect of an increasing population on overall water demand.

Booras et al (2018) and McIntyre et al. (2017) are detailed investigations included in the Sectoral Applications Research Program (SARP) Final Report, Weiss et al. (2017). This project was initiated to help bridge the gap between development of forecast and early warning products by NOAA and adoption and integration of such into water supply utility planning in the Chesapeake Bay region. The primary goal of this study was to develop a Drought Planning Tool (DPT) for the Susquehanna River Basin to inform stakeholder planning and drought coordination activities.

The present study is a preliminary analysis of the potential risk of climate change and demand uncertainty on the City of Baltimore water supply. More comprehensive flow mass analyses for the Baltimore City reservoir/Susquehanna River water supply system, like the recuring 5-year studies of the WMA and Potomac River basin, should be conducted to incorporate the effects of climate change. But the present analysis indicates that the water system could survive a more severe drought than occurred in 2002, with greater withdrawals from the Susquehanna River, earlier imposition of water use restrictions, and optimization of operational methods.

Climate Change and Maryland
Western Shore Coastal Plain Water Supplies

The largest water withdrawals (5,513 Mgd avg) in the State of Maryland are for once through cooling water for thermoelectric plants; however, 96% (5,295 Mgd avg) is taken from saline sources and only 1.2% (61 Mgd avg) of that is consumed[2]. Four coastal counties account for 97% of those withdrawals, with 63% (3,324 Mgd avg) in Calvert County. The second largest use in the State is from public water supply withdrawals. The total in 2015 was 750 Mgd avg, of which 656 Mgd avg was taken from surface water. Of the groundwater used by public water supplies, 85% is withdrawn from Coastal Plain aquifers, with 50% (39.5 Mgd avg) in Anne Arundel County. The Maryland Geological Survey has published numerous reports about the geology and hydrogeology of the Coastal Plain aquifers, with a recent concentration on the confined aquifers of southern Maryland.

Anne Arundel County

In the case of Anne Arundel County, the first study was the Anne Arundel County Report, Maryland Geological Survey (1917), MGS County Reports. The only mention of water resources is that water was withdrawn from the Potomac group by the Brooklyn and Curtis Bay Power and Light Company, and some deep wells that were drilled near Annapolis. It was not until 1948 that water use data were presented by Bennion and Brookhart (1949) for the county. At that time water use was about 750,000 gpd avg in north county, nearly all from the Glen Burnie public supply wells. About 2.25 million gallons per day (Mgal/d) was withdrawn by the U.S. Navy from deep wells. About 90% of the water used by the City of Annapolis was from surface water sources, with the remaining 10% from groundwater. Mack and Richardson (1962), using analytical methods, estimated the potential reliable yields of future public water supplies of all aquifers in Anne Arundel County could reach 65.3 Mgd avg.

The first known digital simulation of drawdowns in a Coastal Plain aquifer, Mack and Mandle (1977), indicated that 70 Mgal/d could be withdrawn from the Magothy Aquifer, producing drawdowns of 225 ft, 250 ft, and 275 ft in Anne Arundel, Charles and Calvert counties, respectively. A caution was given that potential brackish water intrusion in the vicinity of the Severn, Magothy, and South rivers needed additional study. Chapelle and Drummond (1983) performed a simulation of withdrawals from the Aquia and Piney-Point aquifers of southern Maryland indicating that the total yield of the aquifers could be 16.3 Mgal/d.

Mack and Achmad (1986) developed a multi-layer aquifer model to simulate the effects of pumping from the Potomac Group (Patuxent, lower Patapsco, upper Patapsco, and Magothy aquifers) in northern Anne Arundel County and portions of the adjacent counties. In 1965, groundwater pumpage from the aquifers in the model area totaled 40 Mgal/d (16 Mgal/d - Patuxent, 13 Mgal/d - lower Patapsco, 6 Mgal/d - upper Patapsco, and 5 Mgal/d - Magothy). The total ground-water supply for the12-year period from 1965 to 1977 remained at 40 Mgal/d. Pumpage by the Anne Arundel County Department of Public Works (AADPW), other governmental agencies, and industry was expected to total 118 million gallons per day by the year 2000 in the model area. The results indicated that deep cones of depression would be developed in some aquifers, but that the well fields could provide the estimated demand.

[2] From USGS database (Water Use in Maryland) for 2015

Achmad (1991) demonstrated that ground-water withdrawals from the lower Patapsco aquifer increased from 3.80 Mgal/d in 1965 to about 9.70 Mgal/d in 1985. This caused the average baseflow in Sawmill Creek to decline from 19.3 in/yr during the period 1945-51 to 1.2 in/yr in 1985-1988, after the stream gaging station at Glen Burnie was reestablished in 1984. The Sawmill Creek lower Patapsco well field was inactivated in 1989, after which the average baseflow in Sawmill Creek increased to 6.7 in/yr during the period 1989-1995. In 1995, the lower Patapsco wells at the Dorsey Road WTP were inactivated and the average baseflow in the creek increased to 12.6 in/yr during 1996-2010 or 66% of the pre-pumping average. The remaining reduced flow was due to pumping from the other well fields in upper Anne Arundel County. What was the second highest baseflow in the State was restored to approximately the unweighted average statewide baseflow.

Andreasen (2007) conducted digital simulations to optimize groundwater withdrawals through 2044 from the upper and lower Patapsco and Patuxent aquifers in Anne Arundel County. Withdrawals from public-supply wells operated by the AADPW on average totaled approximately 26 Mgal/d in 2002, causing water levels in the county to drop to as much as 90 feet below sea level. Based on data from O’Brien and Gere (2003) average water demand was projected to increase to 73 Mgal/d day by 2040. Water purchased for the City of Baltimore was 7 Mgal/d in 2007. MGS assumed no water was to be purchased from the City of Baltimore by 2025, although O’Brien and Gere (2003) estimated that 19.7 Mgal/d would be purchased from the city in 2043. To meet demand, new well fields were modeled at Withernsea, Millersville, and Chesterfield with capacities of 3.5, 12, and 8.2 Mgal/d by 2040, respectively. Additional wells would also be required at the existing Broad Creek (five wells), Arnold (five wells), Severndale (one well), Dorsey Road (two wells), Crofton Meadows (four wells), and Ft. Meade (two wells) well fields

Simulated available drawdown (or the difference between the pumping water level and the 80% management level) in the upper Patapsco aquifer near the Broad Creek, Withernsea (proposed), Arnold, Severndale, and Chesterfield (proposed) wellfields was reduced to 90, 301, 94, 20, and 56 feet, respectively, by 2044, Figure 9. Simulated available drawdowns in the lower Patapsco aquifer near the Broad Creek, Withernsea (proposed), Arnold, Severndale, Millersville (proposed), Crofton Meadows, and Chesterfield (proposed) well fields were reduced to 407, 680, 464, 164, 48, 160, and 259 feet, respectively, by 2044. Available drawdown in the lower Patapsco aquifer at a location central to wells at Harundale, Crain Highway, Glendale, Quarterfield Road, Telegraph Road, and Stevenson Road was reduced to 40 feet by 2044. Available drawdown in the Patuxent aquifer near the Broad Creek, Arnold, Dorsey Road, Millersville (proposed), Crofton Meadows, Chesterfield (proposed), and Ft. Meade well fields was reduced to 768,800, 198, 325, 512, 625, and 188 feet, respectively, by 2044.

By 2044, simulated baseflow in Sawmill Creek and North River in Anne Arundel County, and the Northwest Branch of the Anacostia River and Western Branch in Prince George’s County decreased on average approximately 6 percent from the simulated 2002 flows due the projected increased withdrawals.

Andreasen (2020) updated the 2007 digital simulation models. In 2018, a relatively small amount of water was imported from the surface-water-sourced Baltimore City water system (average of approximately 0.01 Mgal/d). Projected groundwater withdrawals were expected to increase to about 67 Mgal/d at build-out in 2086, based on the Malcolm Piernie (2016) study, Figure 10: however, the projected buildout in that report extends to 2130+, with a projected demand of 55 Mgal/d in 2086. This would mean that the modeled drawdowns and decreased baseflow in the Andreasen (2020) study need to be reduced by a factor of about 0.82.

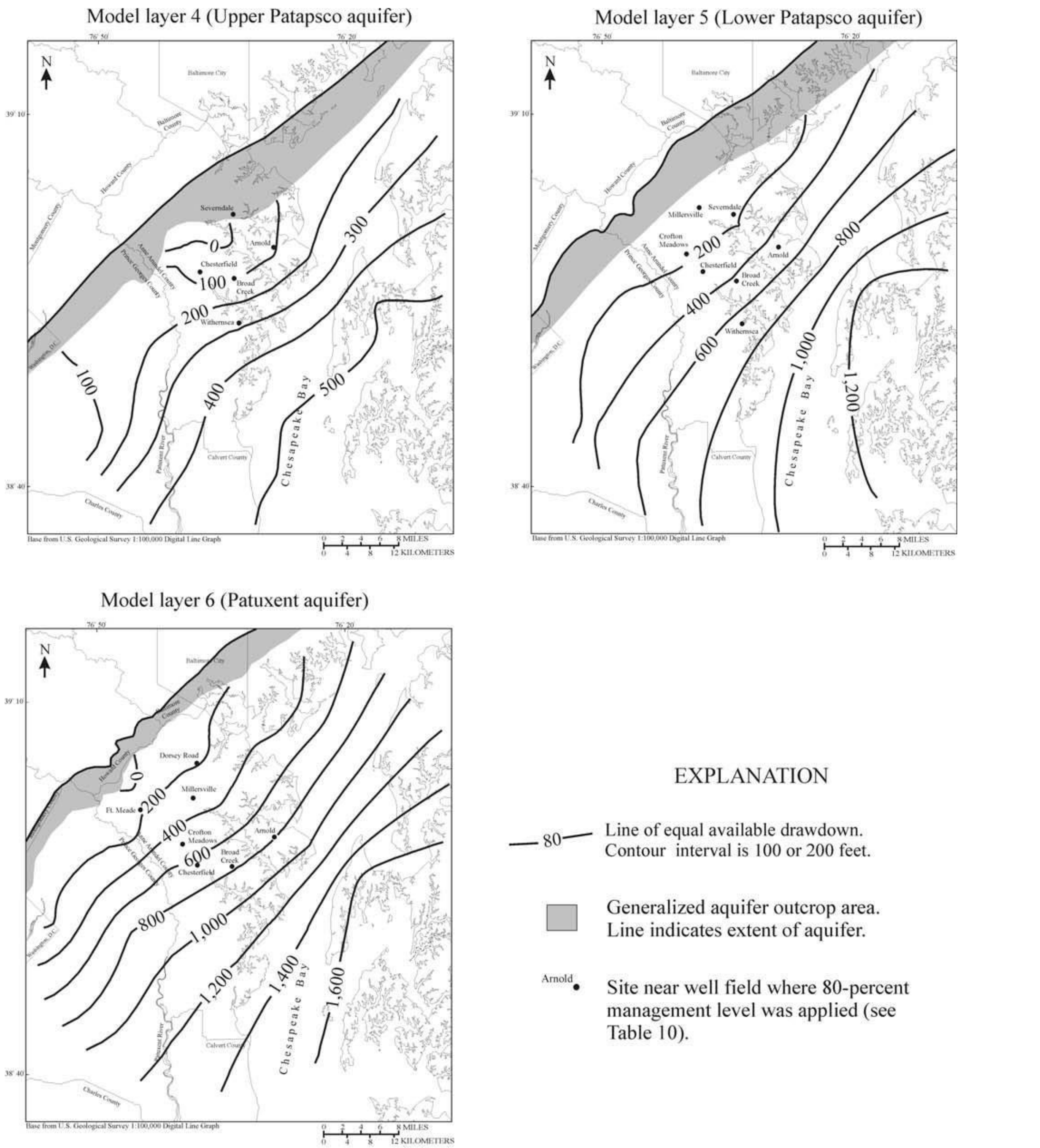


Figure 9. Simulated available drawdown in 2044 for Patapsco and Patuxent aquifers model layers for optimized average-day withdrawals. Reproduced from Andreasen (2007), Fig. 39.

About 33.5 million gallons per day were withdrawn from the AADPW well fields in 2018. Remaining available drawdown in 2018 in the well fields before water levels reach the 80% management levels ranges from 24 to 193 feet in the upper Patapsco aquifer system, 150 to 500 feet in the lower Patapsco aquifer system, and 100 to 960 feet in the Patuxent aquifer system**.** Results of the modeling indicated that a total of 114.4 Mgal/d (adjusted to 139.5 Mgal/d in the present report) can be withdrawn from the well fields before water levels reach 80% management levels in one or more of the aquifers. The simulated maximum withdrawal is about 2.5 times greater than the estimated 2086 demand of 55 Mgal/d and about 4.2 times greater than the amount pumped in 2018. The six major well fields operated by AADPW pumped approximately 33.5 Mgal/d in 2018. Available drawdowns in 2018 in the upper Patapsco aquifer system at the Arnold, Broad Creek, and Severndale well fields were approximately 140, 183, and 24ft, respectively. Remaining available drawdowns in the lower Patapsco aquifer system at the Arnold, Broad Creek, Crofton Meadows, and Severndale well fields were approximately 470, 500,190, and 150 ft, respectively. Remaining available drawdowns in the Patuxent aquifer system at the Arnold, Broad Creek, and Crofton Meadows wellfields were approximately 820, 960, and 500 ft, respectively. The maximum withdrawals result is an approximate 14% (adjusted to 11.5%) reduction in net river discharge from the 2018 amount.

Groundwater travel times from AADPW well fields pumped in the maximum withdrawal scenario were calculated using the groundwater-flow model and the particle tracking code MODPATH. In the upper Patapsco aquifer system well fields, the minimum travel times from model boundaries (water-table aquifer or brackish tidal surface water) is 30 years for Severndale, 75 years for Arnold, and 277 years for Broad Creek. In the lower Patapsco aquifer system well fields, the minimum travel times from model boundaries are 135 years for Arnold, 277 years for Broad Creek, 94 years for Crofton Meadows,144 years for Crownsville, 70 years for Millersville, and 97 years for Severndale. In the Patuxent aquifer system well fields, the minimum travel times from model boundaries are 459 years for Arnold, 375 years for Broad Creek, 244 years for Crofton Meadows, 234 years for Crownsville, and 193 years for Millersville. Considering the substantial overall excess capacity in the maximum estimated yields of the well fields, the travel times indicate that climate change may have limited impacts on the yields of the water system. This could be best be shown by constructing a groundwater flow model demonstrating the long-term effects of variable recharge on the water supply potential of the Anne Arundel County aquifers.

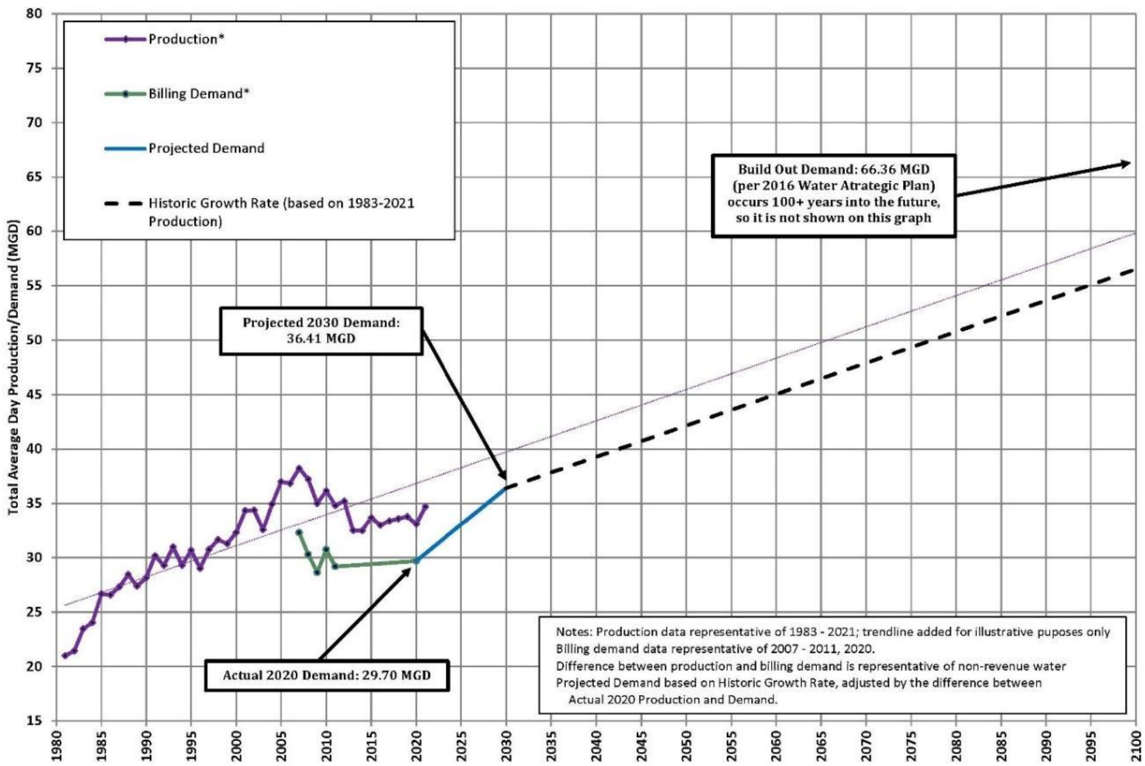


Figure 10. Average day demand projection (historic system production, demand and future growth). Reproduced from Anne Arundel County Master Water and Sewer Plan 2022, Malcolm Piernie (2016), Fig. 3-2.

Other Southern Maryland Counties

Wilson and Fleck (1990) conducted an evaluation of the geology, hydrogeology, water-supply potential, and water quality of the Coastal Plain aquifers in the Waldorf area of Charles County. A digital groundwater-flow model was constructed of the significant aquifers near Waldorf in Charles County (surficial, Aquia, Monmouth, Magothy, St. Charles, and White Plains aquifers and the La Plata aquifer system). The model was calibrated for transient pumping conditions from 1900 to 1985. Pumpage input to the model ranged from a minimum of 0.02 Mgal/d in 1900 to a maximum of 15.6 Mgal/d in 1985. The model was used to simulate head changes through the year 2020 for seven different pumpage scenarios. The results of these scenarios indicated that additional pumpages of 4.2 and 1.9 Mgal/d would result in 95 and 225 ft of additional drawdown in the La Plata aquifer system and White Plains aquifer, respectively. Also, an additional pumpage of about 0.90 Mgal/d from the Waldorf aquifer system would produce additional drawdowns of about 15 ft in the Waldorf area. When the Waldorf aquifer system, White Plains aquifer, and La Plata aquifer system were separately stressed until the 80-percent available drawdown was reached, withdrawal rates of 6.6, 6.1, and 15 .2 Mgal/d, respectively, were obtained, for a total potential reliable yield of 27.9 Mgal/d in the Waldorf area.

Achmad and Hansen (1997) described the hydrogeology and performed a groundwater simulation to determine the water-supply potential of the Aquia and Piney Point-Nanjemoy aquifers of Calvert and St. Mary’s counties. In 1994 withdrawals from the Piney Point-Nanjemoy aquifer were about l.9 Mgal/d in Calvert County and 3.5 Mgal/d in St. Mary’s County. Aquia withdrawals in 1994 were about 3.6 Mgal/d in Calvert County and 4.5 Mgal/d in St. Mary's County. From top to bottom, the hydrogeologic framework consists of the following aquifers and underlying confining units: 1) the water-table Surficial Aquifer (aquifer 1); 2) the confined Piney Point-Nanjemoy aquifer (aquifer 2), and 3) the confined Aquia aquifer (aquifer 3). The transient model was calibrated by matching simulated water levels against 1952, 1980, and 1982 data, which was then verified by matching simulated data against 1991, 1992, 1993, and 1994 water levels. Three pumping scenarios for major ground-water appropriators were simulated: (1), projected 1995 to 2020 pumpage rates based on county water plans and population growth estimates; (2), pumpage using the current (1995) annual average groundwater appropriation permit (GAP) allocation rates from 1995 to 2020; and (3), pumpage using the current (1995) maximum GAP allocation rates applied as annual averages from 1995 to 2020. In the Maximum GAP scenario total pumpage was increased from 8.7 Mgal/d (1995) to 11.1 MgaI/d (2020) in Calvert County and from 11 .9 Mgal/d (1995) to 13.0 Mgal/d (2020) in St. Mary's County.

The potential for increased groundwater withdrawals at six Aquia well fields , three in Calvert County (Chesapeake Ranch Estates, Solomons, and Prince Frederick) and three in St. Mary’s County (Lexington Park, Patuxent Naval Air Test Center, and Leonardtown), was evaluated by comparing drawdowns obtained from the Maximum GAP scenario with permitted management levels (80% of available drawdown). In each case water levels in pumping cells simulated out to 2020 remained above the water management level, although relatively deep simulated water levels ranged from 106 ft below sea level at Prince Frederick to 235 ft below sea level in Lexington Park.

Drummond (2007) prepared an evaluation updating the water-supply potential of the Coastal Plain aquifers in Calvert, Charles, and St. Mary’s counties, emphasizing the upper and lower Patapsco aquifers. Flow-model simulations indicate that projected water demand in Calvert and St. Mary’s Counties through 2030 could be met by increased pumpage from the Aquia aquifer without reducing water levels below the 80-percent management level. Shifting a portion of public-supply withdrawals from the Aquia aquifer to the Patapsco aquifers would result in an increase in available drawdown in the Aquia aquifer in many areas of Calvert and St. Mary’s Counties, with minimal impact on future water levels in the Patapsco aquifers in Charles County. In Charles County, withdrawals from the Magothy aquifer in the Waldorf area cannot be increased significantly above 2002 amounts without lowering water levels below the 80-percent management level by 2030. The relatively shallow depth of the Patapsco aquifers and the proximity of major pumping centers to outcrop/recharge areas limit productive capacity. Future pumpage scenarios result in drawdowns exceeding the 80-percent management level at several Charles County locations, such as Indian Head and La Plata.

Upper Coastal Plain Counties

Drummond and Blomquist (1993) conducted an evaluation of the hydrogeology, water-supply potential, and water quality of the Coastal Plain aquifers of Harford County. A digital ground-water flow model was developed to simulate the response of water levels to projected pumpage in the Coastal Plain aquifers. Almost all recharge to the regional ground-water system comes from precipitation, although small amounts could also be derived from losing reaches of streams and brackish-water intrusion from nearby estuaries. A simulation in which pumping at the 1989 levels was continued until the year 2000 showed no significant additional drawdown from the 1989 potentiometric surfaces. A simulation in which 1989 pumpage was increased by 20 percent showed additional drawdowns of 4 ft in aquifer 2 at the Aberdeen well field and 4 ft in aquifer 3 at the Perryman well field. In a "safe yield" simulation, pumping at the Perryman well field was increased until simulated pumping-water levels were reduced to 80 percent of available drawdown. The total "safe-yield" pumpage at the Perryman well field was 9.2 and 8.3 million gallons per day for average recharge and 10-year drought conditions, or 3.0 and 2.7 times the 1989 pumpage. Analyses of carbon-14 and tritium levels in ground water indicate that residence time in aquifer 2 was less than 50 years and residence time in the deeper confined system is greater than 43 years.

Drummond (1998) described the hydrogeology, conducted groundwater flow simulations, and analyzed groundwater quality data for the upper Coastal Plain aquifers of Kent County.
Five major aquifers supply ground water to users in Kent County:

The Columbia aquifer is the shallowest aquifer and extends over most of Kent County

The Aquia aquifer underlies the Columbia aquifer in most of the southeastern part of Kent County and is semi-confined in most of that area.

The Monmouth aquifer underlies the Aquia aquifer and is confined in most of Kent County. The Magothy aquifer underlies the Monmouth aquifer and is used for small commercial and domestic supplies in the northwestern part of Kent County where the Aquia is absent, and for large community supplies elsewhere in the county.

The upper Patapsco aquifer underlies the Magothy aquifer and is hydraulically connected to it in parts of Kent County. The two aquifers act as a single hydraulic unit.

Pumpage scenarios which simulated projected population growth from 1993 (2.8 Mgal/d) to 2012 (3.0 Mgal/d) indicate regional drawdowns of less than 5 feet in all aquifers. Not included was non-appropriated water for irrigation use.

Pumpage scenarios which simulate projected increases in irrigation pumpage (3.4 Mgal/d) indicate regional drawdowns of as much as 20 feet in the Aquia aquifer and 7 feet in the Magothy and upper Patapsco aquifers.

Columbia (surficial) Aquifer of the Maryland Eastern Shore

The Maryland part of the Delmarva Peninsula, commonly called the Eastern Shore, depends almost entirely on groundwater for its source of supply. The Columbia (surficial) aquifer is one of the most permeable aquifers on the Coastal Plain. It is a major water-supply source in northeastern Dorchester, Wicomico, and Worcester Counties. It is locally important in Caroline, Talbot, and Queen Annes Counties, particularly in areas where paleochannels are present. The total land area is about 3,130 mi^2. The area of the surficial aquifer can be divided into three groundwater provinces, Table 8 and Figure 11, Bachman and Wilson (1984).

The upper-shore province consists of Cecil County below the Chesapeake and Delaware Canal, Kent County, Queen Annes County (except for the section along the Talbot County boundary) and Caroline County north of Ridgely. The aquifer is generally unconfined and thin or has a deep-water table, resulting in a low saturated thickness.

The middle-shore province includes Caroline County south of Ridgely, southeastern Queen Annes County, Talbot County, and the northeastern part of Dorchester County. Local paleochannels exist, with aquifer thicknesses of about 80 ft, resulting in deeper confined and unconfined flow systems, which can provide large scale water supply sources.

In the lower shore, south and east of Preston, Maryland, the aquifer thickens forming paleochannels near Hurlock and Salisbury, reaching an average thickness of 100 ft in the Salisbury area. In the eastern part of the Salisbury paleochannel, the aquifer may be as much as 230 ft thick. Between Salisbury and Ocean City, Maryland, the aquifer becomes mostly confined due to increasing occurrences of overlying low permeability clayey beds.

At the sites for which transmissivity was determined by aquifer tests, hydraulic conductivity ranged from 3 to 300 ft/d, with a mean of 200 ft/d. Sites for which transmissivity was calculated from specific-capacity tests have a range of hydraulic conductivity from 10 to 500 ft/d, with a mean of 90 ft/d. The Columbia aquifer can yield a considerable amount of water, with recorded specific capacities of high-yielding wells ranging from 8 to140 gal/min/ft of drawdown with a mean of 40 gal/min/ft of drawdown.

Dubrow et al. (2019) indicated that in 2011, about 110 Mgal/d of the surficial aquifer was permitted for use, with about 28, 25, 24 and 20 Mgal/d in Dorchester, Wicomico, Caroline, and Worcester counties, respectively. Most of the water was used for seasonal farm irrigation, although it also is used for public water supplies and by many households on private wells. A population of about 244,000 (54% of the total population) in 2015 on the Eastern Shore was served by private wells, primarily from the surficial aquifer. The public water supplies withdrawing water from the surficial aquifer are Salisbury (Paleochannel), Chestertown (unconfined Aquia aquifer), Fruitland, Hurlock, Sharptown, Vienna, as well as the following towns supplied by Worcester County Government: Ocean Pines, Berlin, Briddletown, and Mystic Harbor (Pocomoke aquifer, possibly hydraulically connected to the surficial aquifer). Also in western Somerset County, the Manokin aquifer has possible unflushed brackish water from a subcrop under the Chesapeake Bay, Werkheiser (1990). The water quality of the aquifer is generally good, but where it is unconfined, there is a potential for groundwater contamination.

Table 8. Columbia (surficial) aquifer. Hydrological units. Reproduced from Bachman and Wilson (1984), p. 18.

EXPLANATION →

I – **Columbia aquifer unconfined.** Pensauken Formation and Beaverdam Sand exposed at surface or overlain by the Parsonsburg Sand, or Ironshire or Sinepuxent Formation.

II – **Columbia aquifer confined at depth.** Clay layers present in Pensauken Formation or Beaverdam Sand.

III – **Columbia aquifer confined at surface.** Pensauken Formation and Beaverdam Sand overlain by Walston Silt, Omar Formation, or Holocene lagoon and bay deposits.

IV – **Columbia aquifer confined at surface and at depth.**

Boundary of hydrologic unit; dashed where uncertain.

Approximate boundary of ground-water province.

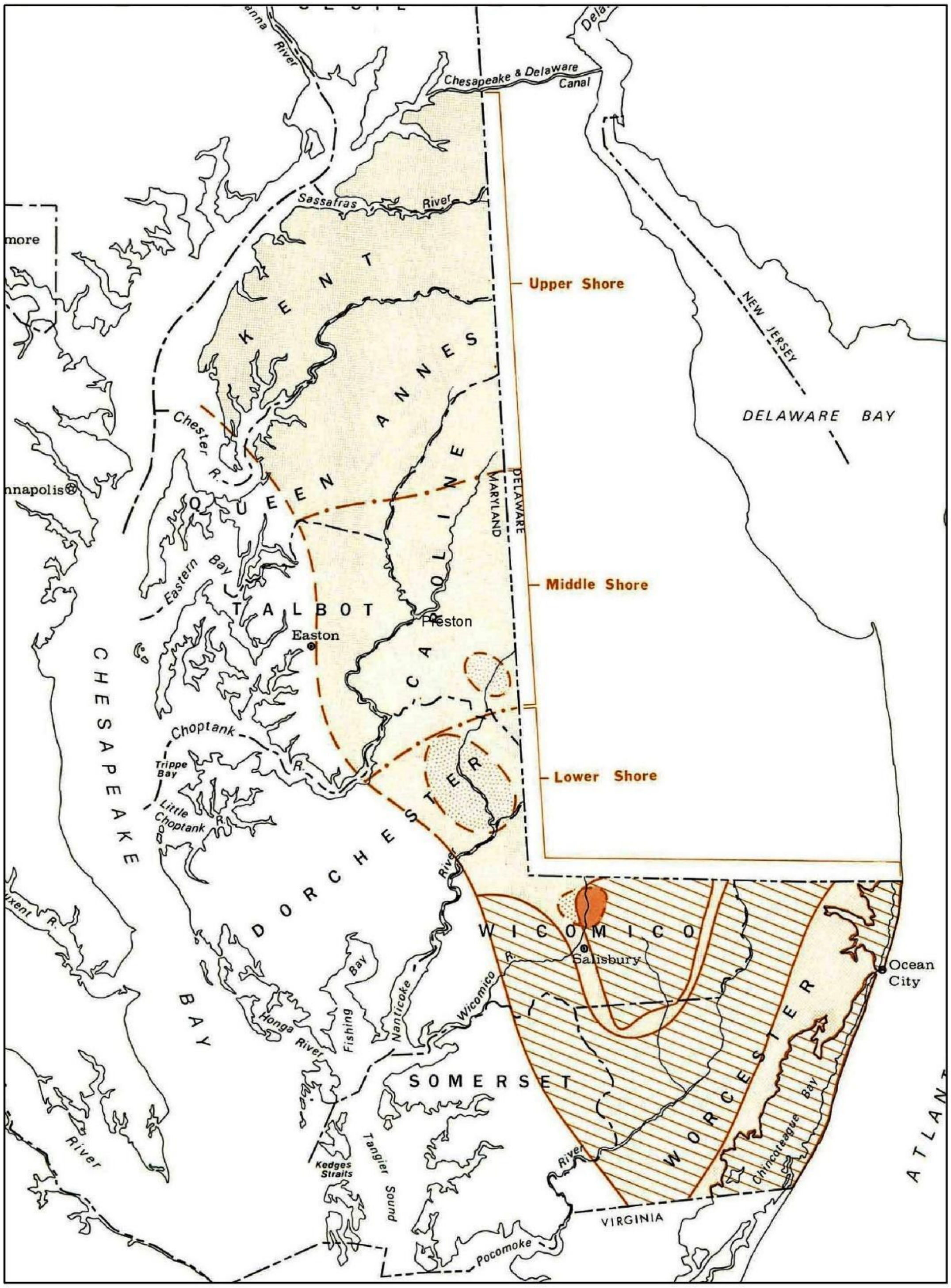


Figure 11. Columbia (surficial) Aquifer groundwater provinces of the Eastern Shore. Hydrological units shown in Table 8. Reproduced from Bachman and Wilson (1984), Fig. 6.

Brackish Water Intrusion and Climate Change in Maryland

In Maryland brackish waters are found in the major rivers and streams along the western and eastern shores by the Chesapeake Bay, and the Fenwick and Assateague barrier islands near Ocean City. Brackish water intrusion is already impacting wetlands, shallow, unconfined aquifers adjacent to salty surface waters and limited portions of Maryland's deeper, confined freshwater aquifers. The State has defined "saltwater intrusion" as the movement of brackish water – as water with a total dissolved-solid (TDS) concentration greater than or equal to 1,000 milligrams per liter (mg/L), Maryland Code (2019). In addition, the EPA has established a secondary standard of 250 mg/L for chloride concentrations in a freshwater aquifer. MDE's regulations prohibit issuing a water appropriation and use permit that causes or contributes to saltwater intrusion into a freshwater aquifer, which has significantly reduced the risk of saltwater intrusion due to over pumping of aquifers. Over the past 100 years, historic tidal records show that sea level has risen in Chesapeake Bay by about one foot and is expected to rise an additional 1.6 ft by 2050, and 4.2 ft by 2100, Boesch et al. (2013).

The few Maryland public supplies using surface water that may be impacted by brackish water due to climate change have intakes on the tidal portion of the Susquehanna River and the nearby North East River.

Most of Maryland's groundwater users rely on aquifers that are not impacted by saltwater intrusion. These include aquifers that are either far from tidal waters (e.g., Piedmont aquifers) or are within deeper, confined aquifers in the Coastal Plain which are for the most part protected from saltwater intrusion by overlying, low permeability clay layers. Generally, Maryland's unconfined aquifer is at a low risk of saltwater intrusion at present; however, there are portions that will be inundated by sea level rise and could be at risk for future brackish water intrusion. The few documented cases of brackish intrusion into water supplies in Maryland are at the Annapolis Neck/Mayo Peninsula, Kent Island, Ocean City, and Indian Head/Bryans Road. Data collected to date indicate that adaption measures have been successful; however, continued monitoring at those sites is needed.

Brackish Water Intrusion, Aquia and Monmouth Aquifers, East-Central Anne Arundel County, Maryland

Hydrogeology

Test wells having chloride concentrations exceeding 5,900 mg/L indicated that a relatively sharp brackish water/freshwater interface in the Aquia and Monmouth aquifers occurred about 200 to 450 feet inland of the shores along Annapolis Neck and the Mayo Peninsula, Fleck and Andreasen (1996). Included in the study was a two-dimensional solute-transport model developed by B. Smith for a Quiet Waters Park test site on Annapolis Neck that simulated hydraulic heads and dissolved-solids concentrations as measured in 1990, producing a simulated equilibrium after 600 years. The results of the model indicated that a shallow well-screen depth could produce a viable freshwater well above the brackish-water interface.

The Aquia and Monmouth aquifers in parts of the county where it crops out near the Chesapeake Bay, or its tributaries, are pumped by domestic and small commercial wells in areas not served by public water supplies. The cumulative effect of pumpage by these many small users has lowered water levels locally in the aquifers by 5 ft or more to near sea level. Water samples were collected from 27 test wells, consisting of 11 Aquia, 10 Monmouth, and 6 Magothy wells. Also sampled were residential wells, consisting of 74 Aquia wells and 1 Monmouth well.

The ground-water-flow model was first calibrated under steady-state conditions, where there was no pumpage input to the model and recharge was held constant. A transient calibration followed that simulated pumpage during the period 1900 through 1990. Most of the groundwater withdrawals from the Aquia aquifer from wells were used for domestic supplies. The amount of water pumped was estimated from census data and a usage rate of 75 gal/d per person. There were no significant withdrawals from the Monmouth aquifer. Figure 12 shows a hydraulic gradient from the landside recharge area of the Aquia aquifer toward the shoreline on Annapolis Neck.

Brackish Water Intrusion

The brackish-water/freshwater interface in the Aquia and Monmouth aquifers was penetrated by test wells at five sites: Londontown Public House Park, Quiet Waters Park, Bay Ridge, Arundel-on-the-Bay, and Mayo Beach Park. No interface was encountered at three other test locations at Annapolis Roads, Hillsmere, and South River Farms Park.

The slope of the interface between well AA De 196 and well AA De 201 in Quite Waters Park was about 0.1. This suggested that the maximum lateral extent of brackish-water intrusion was about 450 ft from shore. At the Mayo Beach Park test well site, on the southern end of the Mayo Peninsula, the brackish water was thought to be from a tidal pond located about 100 ft from the test wells and about 700 ft from the Chesapeake Bay.

On the Mayo Peninsula, high chloride concentrations ranging from 2 to 6,500 mg/L were sampled within a narrow band bordering the shoreline of the South River. Background chloride concentrations in water from the Aquia and Monmouth aquifers on Annapolis Neck and the Mayo Peninsula are generally less than 10 mg/L. The highest concentrations of chloride occurred in water from the Monmouth aquifer and from the lower section of the Aquia aquifer. Virtually the entire upper section of the Aquia aquifer is free of brackish-water intrusion, except in areas within about 100 ft from the shore of Chesapeake Bay. The extent of brackish-water intrusion in the Annapolis Neck area could be due in part to a long history of domestic pumpage. The Arundel-on-the-Bay and Bay Ridge communities are among the oldest in the area. About 95% of all the domestic wells drilled on Annapolis Neck and the Mayo Peninsula during 1970 to 1990 are less than 90 ft deep and would have likely not reached the brackish water/freshwater interface, except for those located within about 250 ft of the Chesapeake Bay. Well drillers, on encountering brackish water typically raise the well casing-screen to above the interface or abandon the well and redrill to the deeper Magothy aquifer, Fleck and Andreasen (1996).

There was no evidence that the Magothy and upper Patapsco aquifers, within the study area, were intruded by brackish water; however, there may be potential for intrusion into the Magothy aquifer as a result of lowering of pressure heads caused by pumpage from both the Magothy and upper Patapsco aquifers, Figure 13. On Annapolis Neck and the Mayo Peninsula, the Magothy aquifer is overlain by the Matawan confining unit, a low permeability clay. On Broadneck, however, the Magothy aquifer subcrops beneath the Severn and Magothy Rivers, providing a potential entry point for brackish-water intrusion.

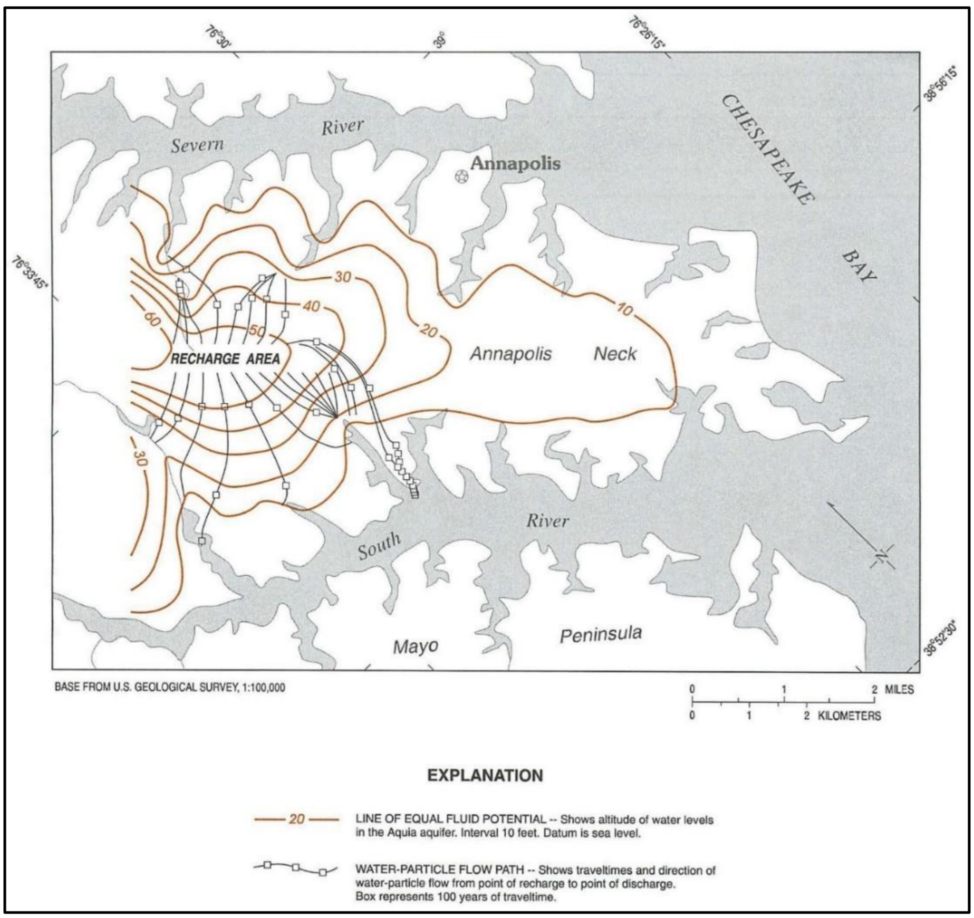


Figure 12. Lines of equal fluid potential and flow paths for water particles in the Aquia aquifer as simulated for pumpage alternative 3, Annapolis Neck. Reproduced from Fleck and Andreasen (1996), Fig. 40.

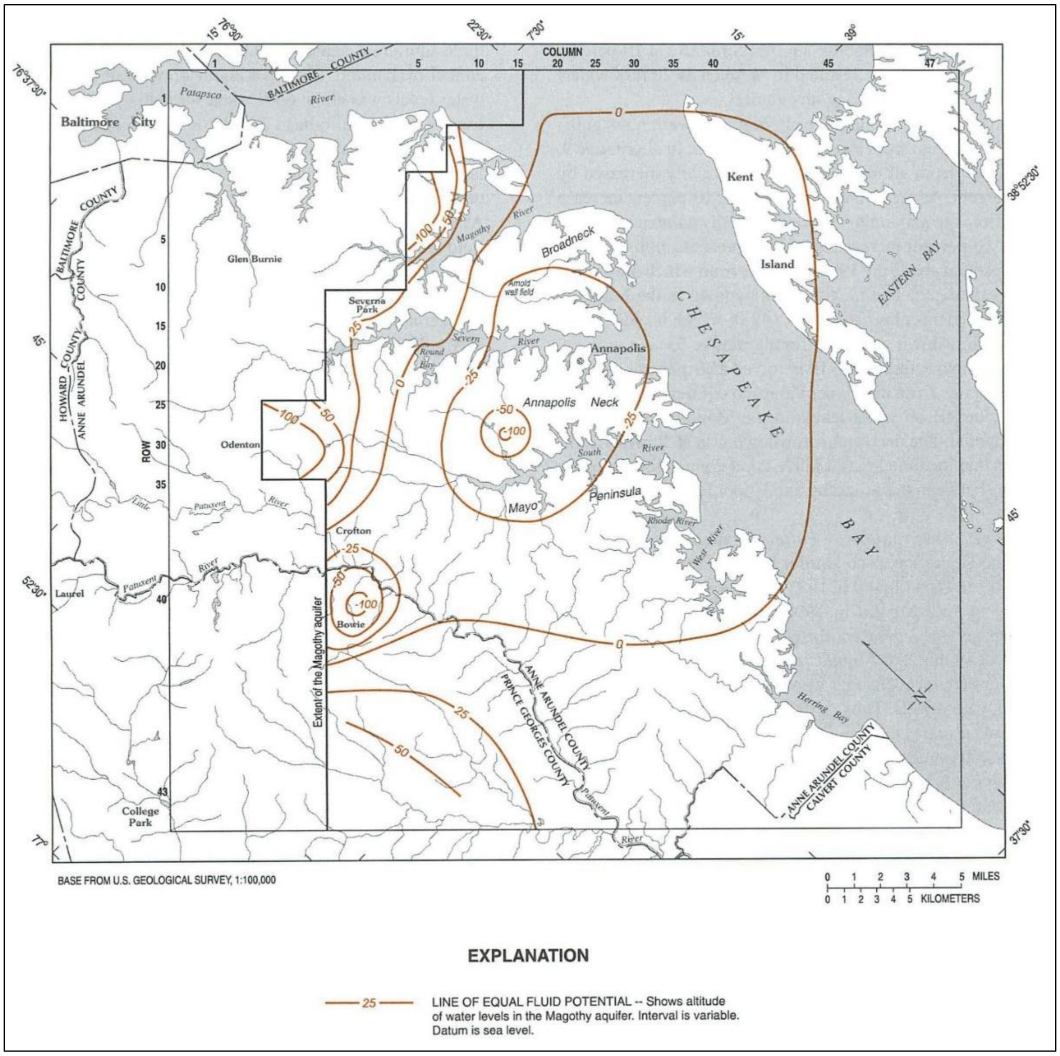


Figure 13. Lines of equal fluid potential for the Magothy aquifer as simulated for pumpage alternative 2. Reproduced from Fleck and Andreasen (1996), Fig. 41.

Brackish Water Intrusion, Patuxent, and Patapsco Aquifers, City of Baltimore, Harbor District, Maryland

Brackish-water contamination of the Patuxent and Patapsco aquifers was a major problem starting in the early 1900's in the City of Baltimore area, Chapelle and Kean (1985). In 1982 there was a circular plume of brackish water in the Patuxent aquifer about 5 miles in diameter centered on the Harbor district, which had enlarged considerably since 1945. Pleistocene erosional channels breached the overlying Arundel Formation confining unit providing a conduit for brackish water to intrude into the aquifer. The Patapsco aquifer was the first one exploited as a source of water in Baltimore. Because the Patapsco aquifer subcrops extensively under the brackish Patapsco River, chloride contamination became a major problem in the early 20th century. Because of that, almost all pumpage from the Patapsco had ceased in the Harbor, Canton, and Dundalk districts by 1945.

Chapelle and Kean (1985) developed a two-dimensional solute transport model to estimate the movement of the brackish-water plume in the Patuxent aquifer based on the following simulations of alternative uses of the aquifer:

(1) The 1982 pumpage rates continue for 50 years.
(2) A 50-year simulation where the 1982 Sparrows Point pumpage doubles and all other pumpage are keep at 1982 rates.
(3) A 50-year simulation where all pumpage in the Baltimore area is discontinued.
(4) A 50-year simulation where 1982 rates of pumpage continue in Baltimore, but pumping from Anne Arundel County well fields produces a cone of depression 100 ft below sea level near Glen Burnie.
(5) A 50-year simulation that continues1982 pumpage in Baltimore and adds 5-Mgal/d pumpage in Marley Neck, Anne Arundel County.
(6) A 50-year simulation of pumpage and freshwater injection in Marley Neck, Anne Arundel County.

Since 1982, virtually all pumpage has ceased in the Sparrows Point area and no production well field or freshwater injection facility has been constructed in the Marley Neck area. After 40 years, there are still plans for those projects, except the proposed Marley Neck well field is about 2.5 miles southwest of the location point in the simulated model and is only proposed to have a capacity of 1.5 Mgal/d, and the freshwater injection site may be near Crofton Meadows, 17 miles southwest of Sparrows Point. Based on this information, the third scenario most likely reflects present day conditions. In that case, the total area of chloride contamination increased slightly from 30 to 31 mi^2, Figure 14, suggesting that ceasing Patuxent pumpage had not significantly reduced the chloride contamination problem. It is possible that as the chloride moved downgradient, it was trapped by the Arundel Formation confining unit and could not escape the Patuxent Formation.

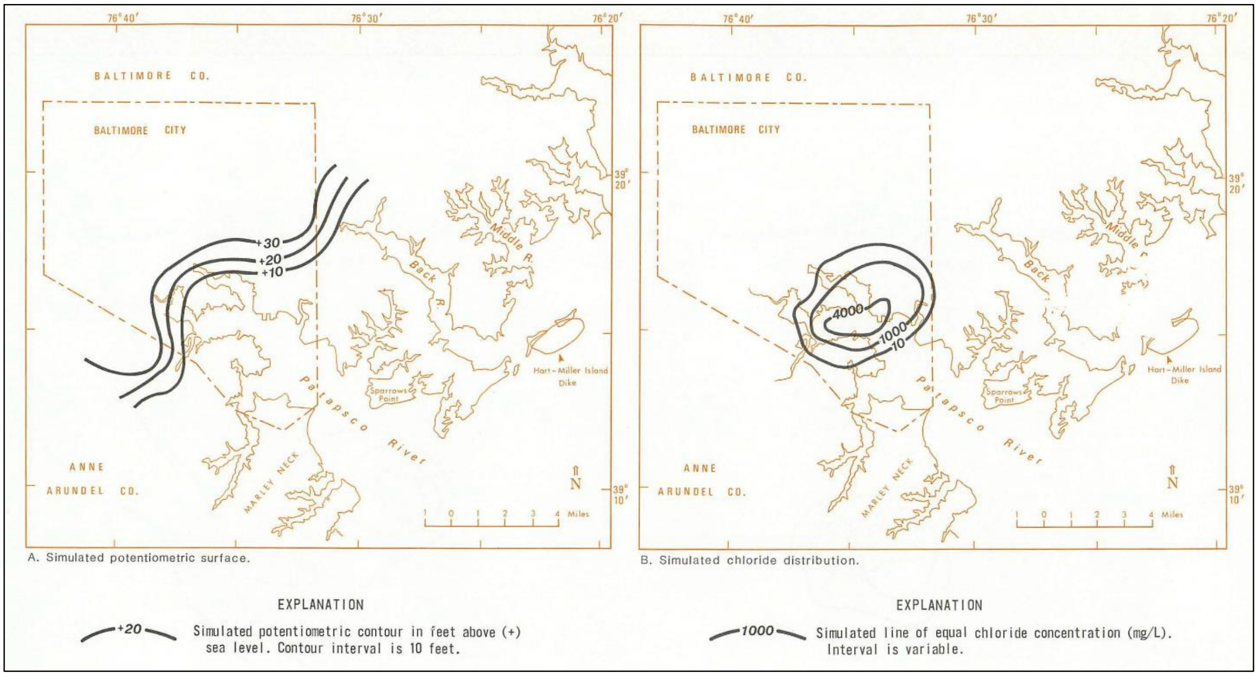


Figure 14. Simulated potentiometric surface and chloride distribution assuming all pumpage in Baltimore stops for 50 years. Reproduced from Chapelle and Kean (1985), Fig. 20.

Brackish Water Intrusion, Potomac Group Aquifers, Indian Head-Bryans Road Area, Charles County, Maryland

In 1989, the static water levels in the confined aquifers at Indian Head ranged from about 55 to 100 ft below sea level, while the pumpage during the 1980's ranged from about 1.5 to 2.0 Mgal/d, Hiortdahl (1997). This produced a cone of depression roughly centered on the Indian Head peninsula, which likely extended several hundred feet under the Potomac River. Based on low tritium concentrations from water withdrawn from wells in 1988, the confined aquifer system was likely recharged before 1952. The background chloride concentration in water in the Potomac Group aquifer system in northwestern Charles County ranged from about 1 to 20 mg/L. The maximum chloride concentration measured in the Potomac Group aquifer system during 1988 was 210 mg/L in water from well CH Cb 34, Figure 15, located within several hundred ft from the Potomac River. The chloride concentration in water from the same well in 1971 had been 95 mg/L. The rapid change in the chloride concentrations suggested long-term monitoring was needed; however, no chloride measurements in well CH Cb 34 can be found after 8/31/1990. The chloride concentration approached but did not exceed the USEPA's secondary (aesthetic) maximum contaminant level of 250 mg/L It is likely that the Arundel Formation may have been truncated, or at least deeply incised, under the Potomac River providing a pathway for potential brackish water intrusion.

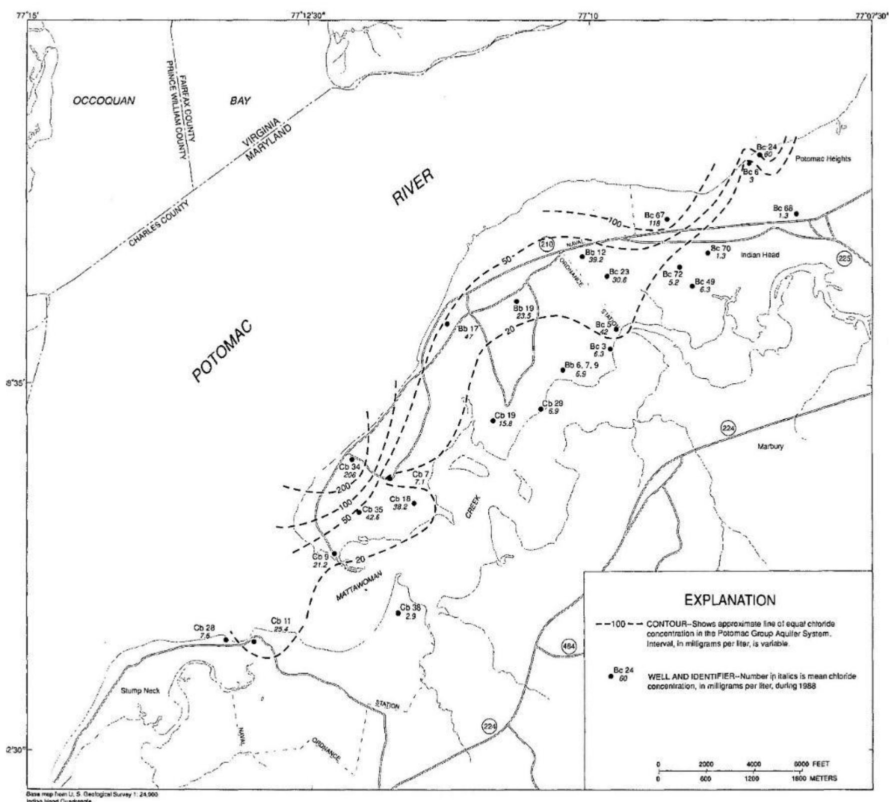


Figure 15. Mean concentrations of dissolved chloride in water from wells sampled during1988. Reproduced from Hiortdahl (1997), Fig. 23.

Brackish Water Intrusion, Aquia Aquifer, Kent Island, Queen Anne's County, Maryland

The Aquia aquifer supplies most of the freshwater needs for Kent Island, Queens Annes County. Water levels in the aquifer dropped from several feet above sea level in the mid-1950's to several feet below sea level in 1984, due to considerable residential and commercial development during the prior few decades, which was expected to continue, Drummond (1988). Throughout the Pleistocene Epoch, periods of worldwide glaciation caused cyclic fluctuations of sea level. During periods of low sea-level stand, rivers cut deep channels into the existing Coastal Plain sediments, Figure 16. Between periods of glaciation, the ice melted, sea level rose, and the channels were filled with sediments. One of the channels removed parts of the Aquia Aquifer and overlying confining unit near the shore of Kent Island and has become a recharge zone of brackish water to the aquifer, Figure 17. Due to major groundwater withdrawals in the Aquia Formation, aquifer water levels were lowered below the head of Chesapeake Bay. Drummond (1988) collected data from 150 wells, that included water levels in 90 wells, and water samples from 75 wells for analysis of chloride, conductivity, dissolved oxygen, and pH.

A ground-water flow model was developed to simulate water levels in response to historic, present, and future pumpage, and a solute-transport model was developed to simulate the distribution and movement of brackish water in the Aquia aquifer. The flow-model area included Kent Island and a large portion of the Eastern Shore, with simulation of pumping centers at the towns of Easton, Oxford, St. Michaels, and Centreville.

The calibration period simulated pumpage from 1895 through 1984. Future pumpage was simulated in nine scenarios in the calibrated model through the year 2005. Although no movement of the brackish-water interface was documented during that study, simulation 1 provided the best estimate of future water demand indicating that the freshwater/brackish-water interface will move about 440 feet inland during the 21-year simulation period (1984-2005). It is noted that neither the calibration period nor simulation 1 included water withdrawn for agricultural irrigation uses. One reason would be that Water Appropriation or Use Permits were not required for agricultural uses until 1989. It then took several years to issue permits for the existing uses and agricultural water use reporting did not start until 1995. The USGS has been estimating irrigation water use in Queen Anne's County since 1950, and the approximate average use for irrigation during the calibration period (1.3 Mgal/d) was nearly equal to the pumpage used in the model (1.6 Mgal/d) for Queen Anne's County. Had the irrigation pumpage been included in the model calibration, then the expected movement would have been substantially slower than the rate resulting from the published model.

Brackish water with chloride concentrations greater than 1,000 mg/ L is present in the Aquia aquifer within 0.25 mi of the Chesapeake Bay shore from Love Point in the north to at least as far south as Prices Creek. Brackish water with lower chloride concentrations is present farther inland on the northern and southern tips of the island. A distinctive vertical zonation of chlorides was found throughout the zone of brackish water. Water with high chloride concentrations (as much as 7,000 mg/ L) is present in the lower part of the Aquia aquifer, grading upward to freshwater (less than 10 mg/ L chloride) or water with low concentrations of chloride at the top of the formation. No general trend of increasing concentrations with time was documented, possibly due to the lack of historical chloride data in critical areas.

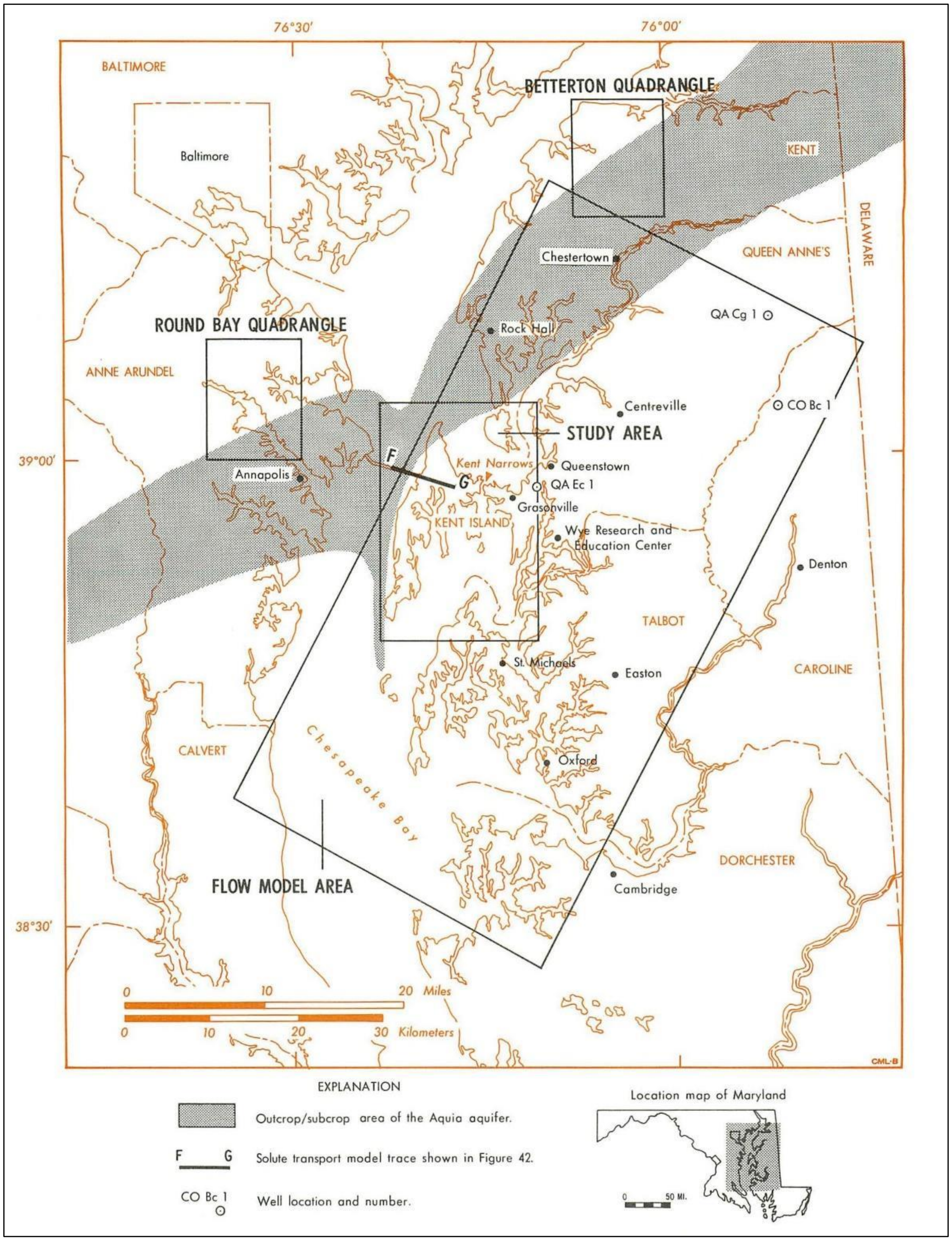


Figure 16. Locations of study area, flow-model area, solute-transport model trace, and outcrop/subcrop area of the Aquia aquifer. Reproduced from Drummond (1988), Fig. 1.

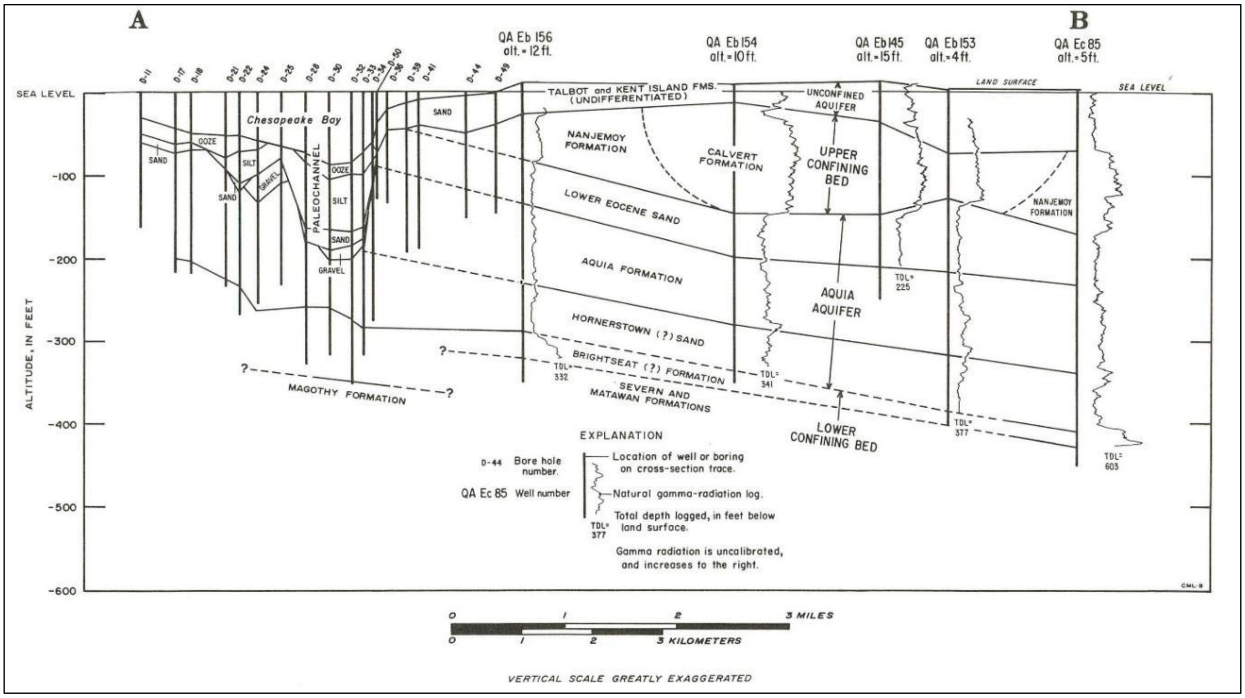


Figure 17. Hydrogeologic section A-8 showing major hydrogeologic units in the Kent Island area based on gamma logs and test borings. Reproduced from Drummond (1988), Fig. 3.

Drummond (2001) updated the 1988 MGS Kent Island study, but the 2001 flow model did not simulate solute transport, so it could not be used to directly determine rates that the brackish-water interface would move. Flux calculations did provide a qualitative means of comparing the potential impact of future pumping scenarios. Irrigation water use was included in the calibration and simulations. All future simulations produced positive flux values, which indicated that ground water will move inland in all the pumpage scenarios. Even when the existing pumpage was reduced by 20 percent, landward flow occurred. Quadrupling irrigation pumpage in Queen Anne's and Talbot Counties had a greater impact on any brackish-water movement than other simulations except with the doubling all pumpage in the model area.

Ground water with elevated chloride concentrations was present in the upper part of the Aquia aquifer on northern and southern Kent Island, and a narrow strip along the Chesapeake Bay on the central part of the island, Figure 18. At the northern tip of Kent Island, the entire section of the Aquia aquifer contains brackish water. Monitoring ground water in a network of wells on Kent Island since 1984 did not indicate an overall, consistent trend in the change of chloride concentrations, but did identify an area where concentrations are generally increasing. Variations in water chemistry caused by sporadic but widespread pumping, fresh-water leakage from overlying aquifers, and pre-pumping invasion of brackish water from the Chester River and the Eastern Bay may have obscured an overall increase in chloride concentrations. Domestic wells supply about 80% of the population in Queen Anne’s County, so if leakage from overlying aquifers is a factor, then septic tank discharges would supply several Mgal/d of effective recharge to the Aquia Aquifer.

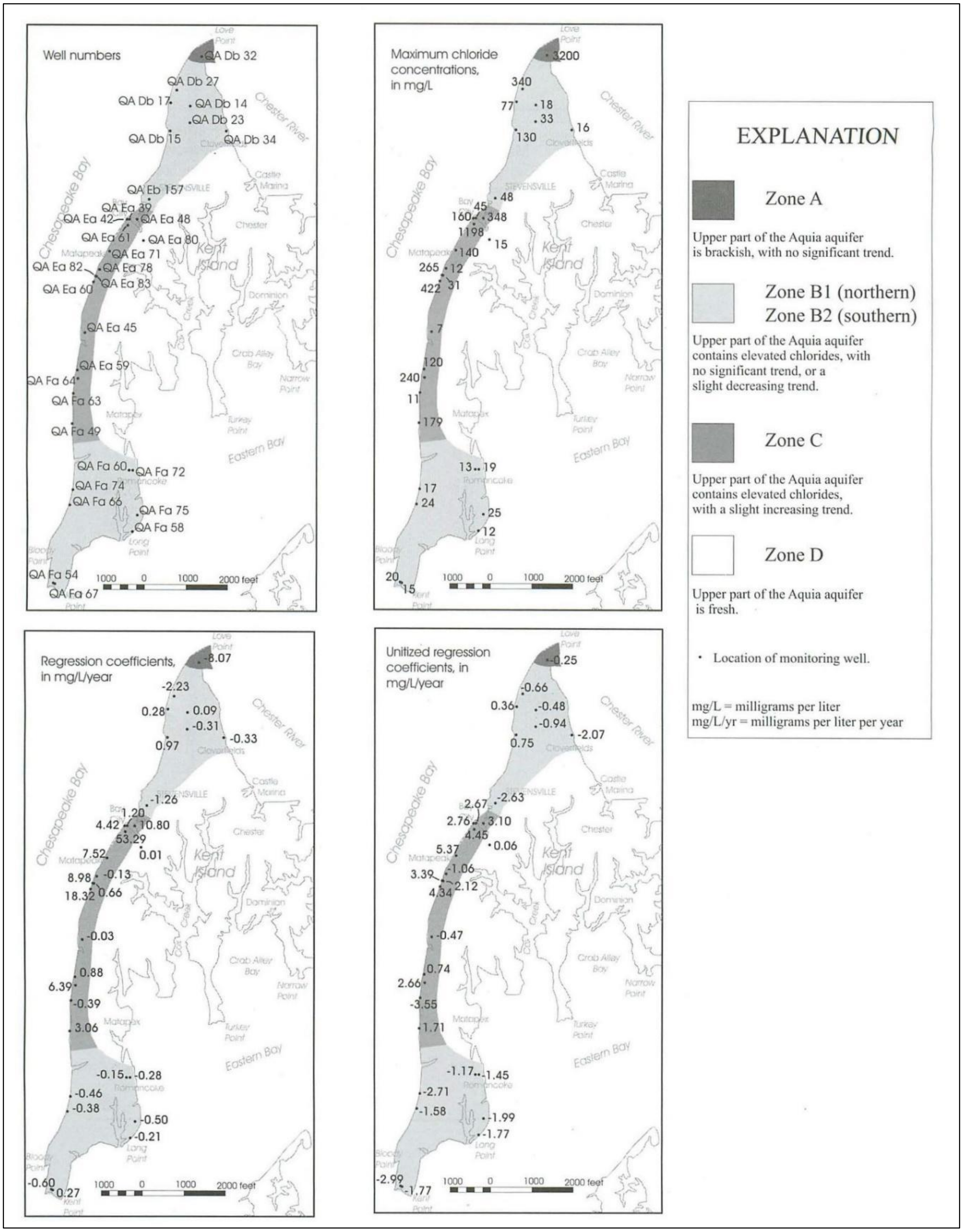


Figure 18. Maximum chloride concentrations, chloride regression coefficients, and unitized regression coefficients of chloride concentrations for wells screened in the upper part of the Aquia aquifer on Kent Island. Reproduced from Drummond (2001), Fig.35.

In 1988 the Maryland Water Resources Administration introduced a water-management strategy, which prohibited all new groundwater uses on Kent Island, and those new users east of Kent Island but west of the Wye River proposing to use more than 1000 gpd from the Aquia aquifer. New appropriations of more than 10,000 gpd for users east and south of this area, including Centreville, Easton, and Tilghman Island, were also scrutinized for potential contribution to brackish-water intrusion on Kent Island, Figure 19. This policy could be another reason that the projected pumpage used in the 1988 solute-transport model did not occur.

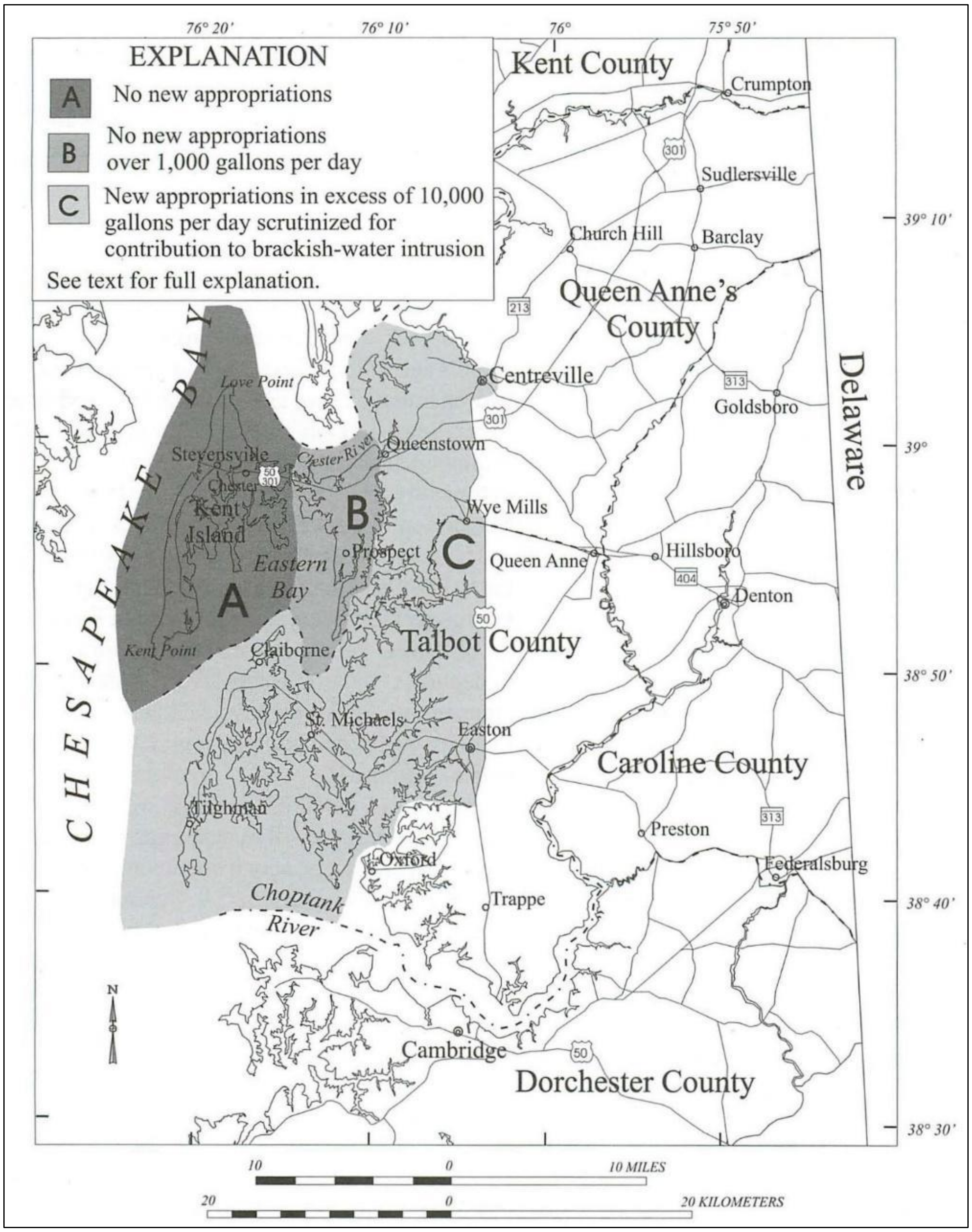


Figure 19. Location of the study area with water-use restriction zones designated for the Aquia aquifer. Reproduced from Drummond (2001), Fig. 1.

Bolton and Gemperline (2018) updated the data from the monitoring network on Kent Island established in 1986 based on wells sampled in Drummond (1988) study. The wells were initially sampled annually or semiannually until 2015, when sampling was changed to a two-year interval. Thirteen observation and 18 residential/commercial wells in the monitoring network were sampled in August and September 2017. Chloride concentrations in some wells in the Bay City/Matapeake Estates areas continue to show an overall increase. Changes in chloride concentrations were generally not seen in samples from the lower Aquia aquifer, where salinities are much higher and screened intervals are farther below the freshwater/brackish-water interface. The lower Aquia aquifer is still brackish along the entire bay shore. About ¼ mile inland from the bay shore the entire section of the Aquia is fresh and does not show evidence of an increasing trend. Increasing trends in chloride concentrations may indicate slight landward movement of the brackish-water interface, but variations mask the trends on parts of Kent Island.

Brackish Water Intrusion, Ocean City-Manokin Aquifer, Ocean City, Worcester County, Maryland

The Maryland Geological Survey (MGS) has conducted several major studies addressing the potential for extensive brackish water intrusion impacting the public water supply of Ocean City, Worcester County. The first was Weigle (1974) who described the Manokin and Ocean City aquifers as poorly separated and leaking such that they acted as a single hydrologic unit. In June 1972, the Ocean City water supply was obtained solely from wells in the Ocean City aquifer.

In 1971, an estimated cone of depression in the Ocean City-Manokin potentiometric surface attained a diameter of more than 12 miles during the summer while pumping the city wells at 3 Mgal/d, and it was inferred that the potentiometric surface was below sea level approximately 3 miles offshore from Ocean City, Weigle (1974). However, no evidence of salt-water intrusion was found in the Ocean City-Manokin aquifer system, but it was speculated that brackish water from the adjacent ocean and bays or underlying salty aquifers could eventually enter the aquifer system at Ocean City. Although its distance from land was unknown, a brackish water/ freshwater interface in the Manokin was proposed to lie offshore from Ocean City, approximately parallel to the coastline. The author indicated that, if the interface was several miles offshore, the time of arrival would probably be so great that it would be irrelevant, such that contamination of the aquifer by brackish water seemed unlikely. To determine the position of the interface, it was suggested that test wells be drilled at the beach and offshore from Ocean City.

A follow-on study was conducted by Weigle and Achmad (1982). The cone of depression in the potentiometric surface of the Ocean City and Manokin aquifers was again estimated to reach 12 miles while pumping at the Ocean City wells at an average of 3.45 Mga/d in 1976 and 8.1 Mgal/d in August of that year. The potentiometric surface was inferred to be below sea level as far as 6 miles offshore of Ocean City.

A groundwater flow model was calibrated against six years (1971-1976) of historical pumpage and water level data, and then used for the simulation of alternate groundwater development plans. The model showed that dispersal of pumping centers would reduce the amount of drawdown by spreading out the cones-of-depression. Simulated withdrawals of additional water from well fields at Gorman Avenue, the Isle of Wight, 100th Street, and 66th Street, Achmad and Wilson (1993), Figure 20, appeared to produce more moderate drawdowns than the other pumping schemes that were run on the model. It was not a solute-transport model and could not evaluate the movement of brackish water in the aquifers, either from offshore or upconing by leakage from other aquifers. The projected water demand in 2000 was 16 Mgal/d during the month of maximum use and an annual average of 8 Mgal/d.

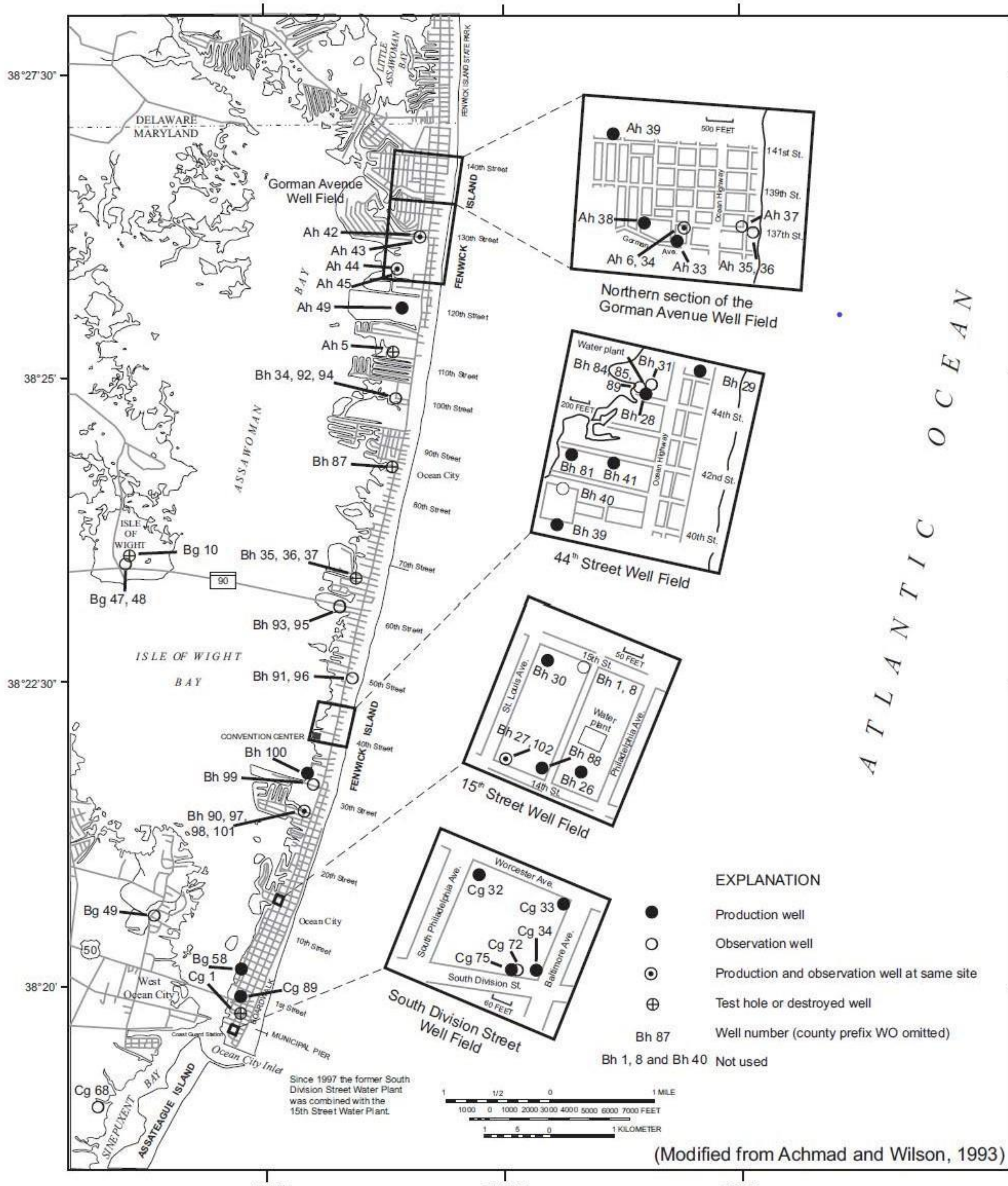


Figure 20.-Locations of test holes, production, and observation wells, and well fields in Ocean City, Maryland, Reproduced from Achmad and Wilson (1993), Fig. 2.

Under the past pumping conditions, there was no clear evidence of increasing chloride concentrations found in the Ocean City, Pocomoke, or Pleistocene aquifers. However, slightly brackish water occurs in the basal part of the Manokin aquifer in the vicinity of Gorman Avenue, near the northern end of Ocean City. Brackish water had apparently entered the basal part of the Manokin from the underlying St. Marys Formation, a clayey confining bed; however, the authors indicated the source of brackish water could also be associated with an offshore brackish water/freshwater interface in the Manokin aquifer. The Ocean City-Manokin aquifer system was traced seaward, tentatively, more than 7 miles east of Ocean City, based on the results of offshore acoustical profiling of sub-bottom sediments in May 1977 and offshore test drilling in August 1977. A sample of freshwater (231 mg/L) was collected at a depth interval of 228-259 ft in a core taken from test well 6008, 8.8 miles off the Ocean City shoreline.

In a third study, Achmad and Wilson (1993) indicated that at the Town of Ocean City's 44th Street well field chlorides in the Ocean City aquifer rose from about 70 mg/L in 1975 to about 215 mg/L in 1988 due to upconing of brackish water from the underlying Manokin aquifer.

A groundwater flow model was constructed to determine the effects of increased pumpage on the groundwater flow system at Ocean City. Projected annual average water demand for Ocean City was expected to increase from about 5.6 Mgal/d in 1990 to 9.1 Mgal/d in 2010. The 2010 rate was assigned to the model to simulate the projected expected amount of pumpage required from the Ocean City well fields. The increased pumpage, approximately 1.6 times the recorded 1990 pumpage, expanded and deepened the cones of depression in the Manokin, Ocean City, and Pocomoke aquifers.

A plume of fresh to slightly brackish water extends offshore in the Ocean City-Manokin aquifer system, which the solute-transport model was able to simulate and was used as an initial condition for calibration (1900-1990) and predictive runs (1990-2010). Simulated pumpage of 2.6, 3.3, and 4.4 Mgal/d for 20 years from the Ocean City aquifer at the 44th Street wellfield resulted in chloride concentrations of approximately 230, 235, and 243 mg/L in 2010, suggesting the upper range of acceptable pumpage at the 44th Street well field. About 20 percent of the water pumped from the Manokin aquifer at the Gorman Avenue well field comes from the offshore part of the freshwater-saltwater mixing zone and less than 0.05 percent is upward leakage from the underlying brackish Choptank aquifer. The remaining 80 percent comes from freshwater recharge areas. Simulating pumpage of 4.5 and 9.0 Mgal/d from the middle and upper parts of the Manokin aquifer at the Gorman Avenue well field resulted in chloride concentrations of approximately 170 and 185 mg/L.

Mass balance calculations for the pumping cells indicated that lateral encroachment from the offshore part of the freshwater-saltwater mixing zone was likely the major source of brackish water in the Manokin aquifer at the Gorman Avenue wellfield. At the 44th Street well field, mass balance calculations for the pumping cell indicated that annual average pumping rates greater than 1.6 Mgal/d would result in increasing chloride concentrations in the Ocean City aquifer because of greater upward leakage from the brackish Manokin aquifer.

A cross-sectional solute-transport model was developed for the 44th Street and Gorman Avenue well fields to simulate chloride distributions in the coastal aquifers. The simulation produced an offshore plume of fresh to brackish water in the Ocean City Manokin aquifer system that extended about 13 miles offshore from Ocean City.

Because the chloride concentrations were approaching the recommended 250 mg/L limit in Bh 28, pumpage from the 44th Street well field was reduced to 1.6 Mgal/d in 1990. The water-development plan for Ocean City, Whitman, Requardt and Associates (1989), suggested maintaining an average daily pumpage of 2.6 Mgal/d at the 44th Street site for the 1992-2010 period, which was then used in the first simulation of the model. A 1.0 Mgal/d increase in pumpage for the simulation period 1992-2010 increased chloride concentrations by approximately 30 mg/L to about 230 mg/L. Additional simulations at the 44th Street site were made to determine the highest pumping rate that could be sustained before simulated chloride concentrations exceeded 250 mg/L. Simulated 1992-2010 pumping rates of 3.3 and 4.4 Mgal/d produced chloride concentrations of 235 and 243 mg/L respectively.

In order to show the effects of an average daily pumping rate of 4.4 Mgal/d at the 44th Street well field, the 2010 chloride concentration isochlors were overlain on the 1990 chloride isochlors using the 1984-1990 pumping rate of 2.1 Mgal/d. Significant shifts in the position of the isochlors occurred in the Ocean City and Manokin aquifers, producing isochlor shifts of a maximum of about 1 to 1.5 miles in 20 years. At that rate, it would take about 173 to 260 years for the offshore brackish water / freshwater interface to reach the Ocean City shoreline.

One significant problem is that the actual water demand in 2010 of 5.5 Mgal/d was substantially less than the projected demand in the groundwater flow model of 9.1 Mgal/d and has since declined to about 4 Mgal/d at present, Figure 21. The projected water demand was based on an extrapolation of the rapid growth in demand following the severe economic recession of the early 1980's. The same pattern was noted in other areas, especially the Washington Metropolitan Area and Anne Arundel County. Since the actual use in 2010 was only about 60% of the projected use, then the rate of movement of the brackish water/freshwater interface would be about 0.6 to 0.9 miles in 20 years, or it would take about 290 to 430 years for the interface to reach the Ocean City shoreline. A more reliable method for estimating future demand for the Ocean City public water supply is needed, but it appears there is no immediate danger of a major brackish water intrusion event.

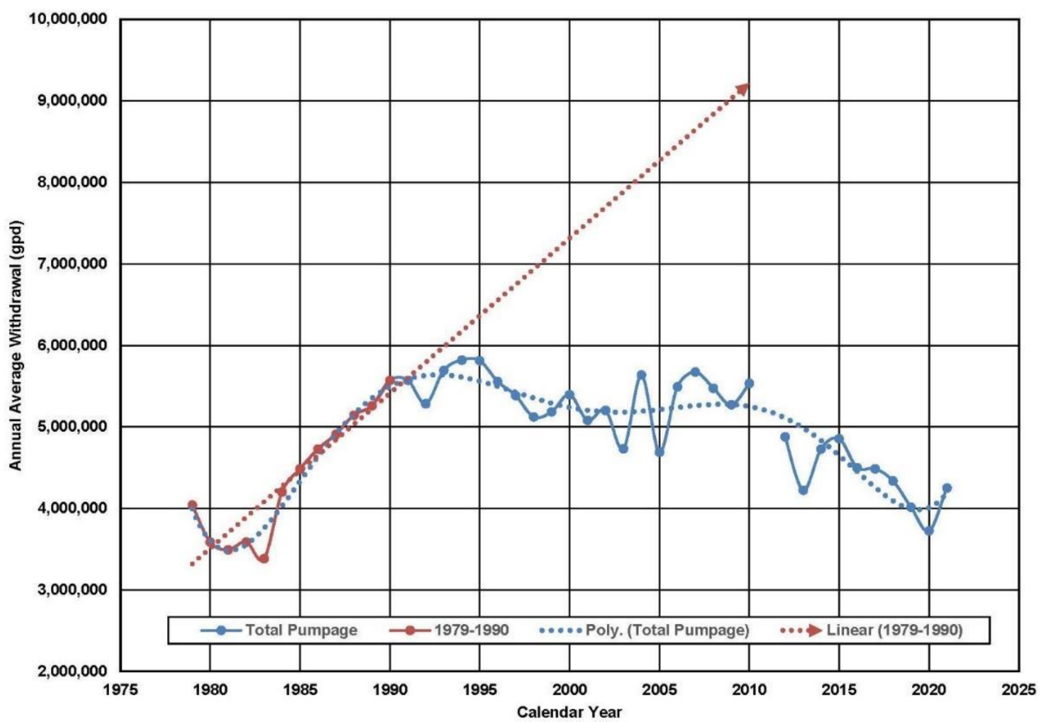


Figure 21. Annual average reported pumpage (water use) Ocean City public water supply for the period1979 to 2021, with polynomial trendline and linear trendline for 1979 to 1990.

Water use is reported to the MDE Water Supply Program only by the individual Ocean City and Manokin aquifers and not by separate well fields. The best information is that all or nearly all the water withdrawn from the Manokin aquifer is taken at the Gorman Avenue well field, while all the water withdrawn from the Ocean City aquifer is taken at the 15th and 44th Street well fields, Table 9. Two Manokin wells at the 15th Street plant appear to not be in service, Whitman, Requardt and Associates (2018). Water use from the Ocean City aquifer reached a peak of 4.3 Mgal/d in 2010, then steadily declined to 2.4 Mgal/d in 2020, Figure 22. While use in 2020 may be related to the Covid pandemic, it is noted that the pre-and post-pandemic uses were only 2.8 Mgal/d. The average reported water use from the Manokin aquifer from 2005 to 2021 was a relatively constant 1.3 Mgal/d. The present total water use is less than ½ of the projected water use in 2010, suggesting that the movement of the brackish water/freshwater interface is much slower that the model indicated, and likely no immediate threat to the Ocean City public water supply.

Table 9. Production wells and well fields in Ocean City, Maryland (1991). Reproduced from Achmad and Wilson (1993), Table 5.

Table 5.—Production wells and well fields in Ocean City, Maryland (1991)

Maryland Geological Survey Well Number	Town of Ocean City Well Designation+	Aquifer	Street Location	Date Drilled
		South Division Street well field		
WO Cg 32	A	Ocean City	Worcester St.	1955
WO Cg 33	C	Ocean City	Worcester St.	1955
WO Cg 34	B	Ocean City	South Division St.	1967
WO Cg 75	D	Manokin	South Division St.	1984
		15th Street well field		
WO Bh 26	A	Ocean City	15th St.	1957
WO Bh 27	B	Ocean City	14th St.	1960
WO Bh 30	C	Ocean City	14th St.	1967
WO Bh 88	D	Manokin	14th St.	1984
		44th Street well field		
WO Bh 28	A	Ocean City	44th St.	1963
WO Bh 29	B	Ocean City	45th St.	1963
WO Bh 39*	F	Ocean City	39th St.	1969
WO Bh 40*	E	Ocean City	42nd St.	1969
WO Bh 41	C	Ocean City	42nd St.	1969
WO Bh 81	D	Ocean City	42nd St.	1971
		Gorman Avenue well field		
WO Ah 33	B	Manokin	Gorman Avenue	1972
WO Ah 34	A	Manokin	137th St.	1972
WO Ah 38	C	Manokin	137th St.	1975
WO Ah 39	D	Manokin	141st St.	1975
WO Ah 43	E	Manokin	130th St.	1989
WO Ah 45	F	Manokin	125th St.	1990

+ The town of Ocean City uses both the well field name and a letter to designate the individual production wells; for example, the 44th Street A well, the Gorman Avenue D well.

* Bh 39 and Bh 40 were originally drilled to supply the Ocean City Convention Center's cooling and heating systems. These wells were taken over by the Ocean City Water Department in 1986.

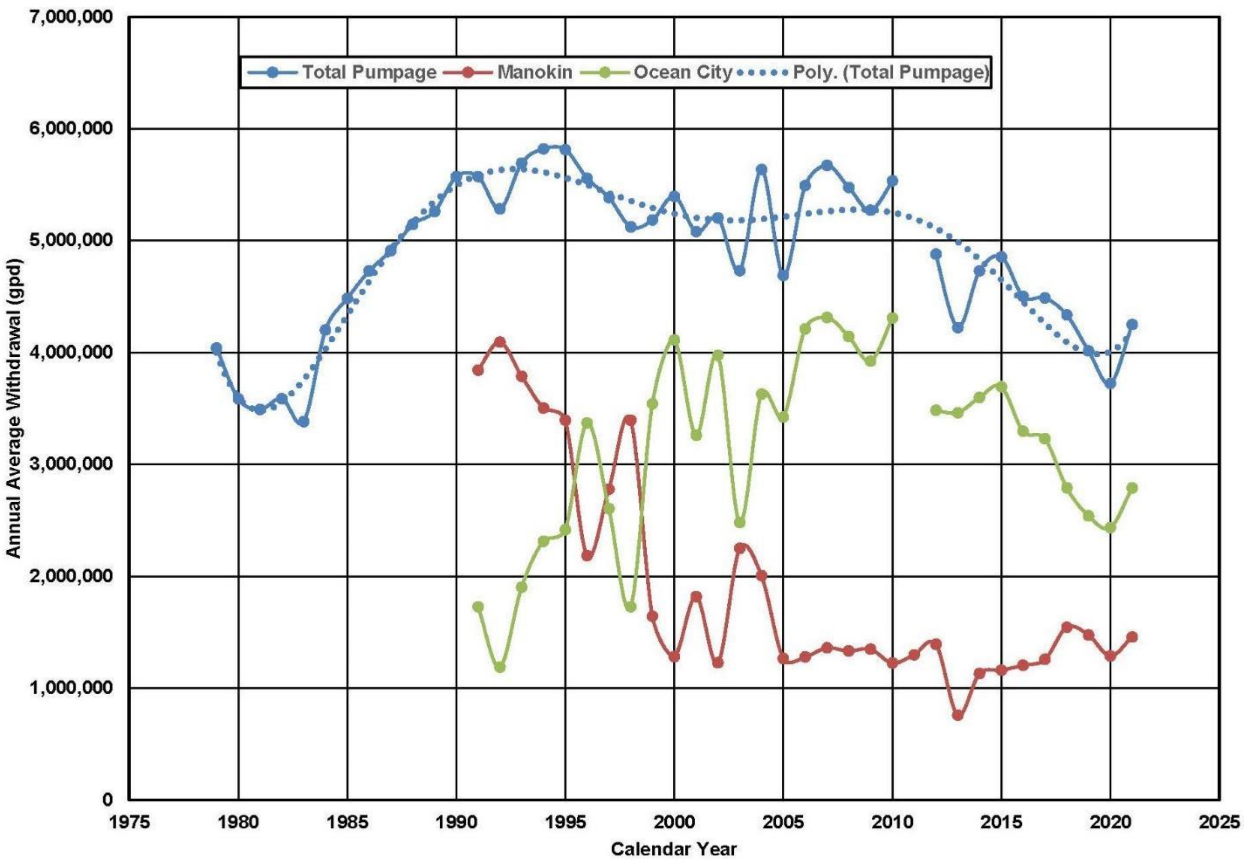


Figure 22. Total annual average reported pumpage (water use) Ocean City public water supply for the period 1979 to 2021, with polynomial trendline, pumpage from the Manokin and Ocean City aquifers for the period 1991 to 2021.

In the final study, Achmad and Bolton (2012) constructed a groundwater flow model and three two-dimensional solute transport models of the aquifer system beneath Ocean City, using hydrogeologic information, historical water-levels, and chloride data collected through 2005. The models simulated water levels and chloride concentrations at Ocean City's well fields, Figure 20 and Table 9, through 2025, using Ocean City's future development plan of maximum withdrawals of 6 Mgal/d from the 15^{th} Street well field, 4 Mgal/d from the 44^{th} Street well field, and 8 Mgal/d from the Gorman Avenue well field. The higher use at the 15^{th} Street and Gorman Avenue plants reflects that the chloride concentrations at those fields had not approached 250 mg/L, while the lower use at the 44^{th} Street plant was due to the potential of brackish water intrusion by upconing from the Manokin aquifer. The total maximum use of 18 Mgal/d is the equivalent of an average annual use of 7.9 Mgal/d, which is somewhat less than the projected 2010 demand of 9.1 Mgal/d used in Achmad and Wilson (1993) study and considerably less than the reported pumpage of 4.2 Mgal/d in 2021.

At the 15^{th} Street well field the simulated chloride concentrations were 55 to 60 mg/L in 2025, an increase of about 5 mg/L over 2005 levels, Figure 23. Chloride concentrations from samples taken in 2016 and 2017 were 45-51 mg/L, Whitman, Requardt & Associates (2018).

At the 44th Street well field, Figure 24, the 2025 simulated average chloride concentrations were 150 to 250 mg/L compared to about 125 to 215 mg/L chloride in 2005. Chloride concentrations from samples taken in 2016 and 2017 were 100 to 260 mg/L. Elevated levels of 220 and 260 mg/L was taken from Well C (Bh 41) in 2016 and 2017, respectively, which were significantly higher than the simulated value of 153 mg/L, and the measured values of 80 mg/L and 124 mg/L in 1980 and 2005, respectively. The significant increase in chloride concentrations in Well C is likely due to upconing of brackish water from the Manokin Formation, rather than migration of brackish water from offshore.

At the Gorman Avenue well field, Figure 25, the highest simulated average chloride concentration in the Gorman Avenue well field was about 150 mg/L in 2025, compared with about 130 mg/L in 2005. Chloride concentrations from samples taken in 2016 and 2017 were 100 to 130 mg/L, likely because of the low amount of water (1.2 Mgal/d) reported withdrawn from the Manokin aquifer.

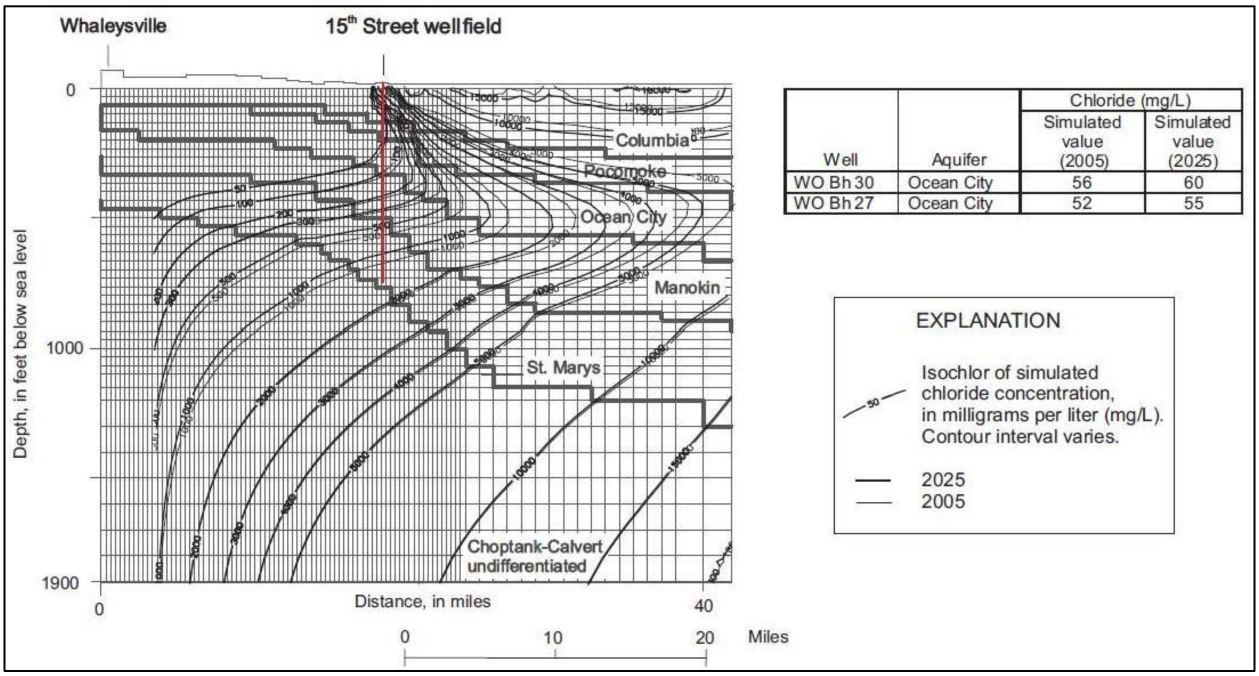
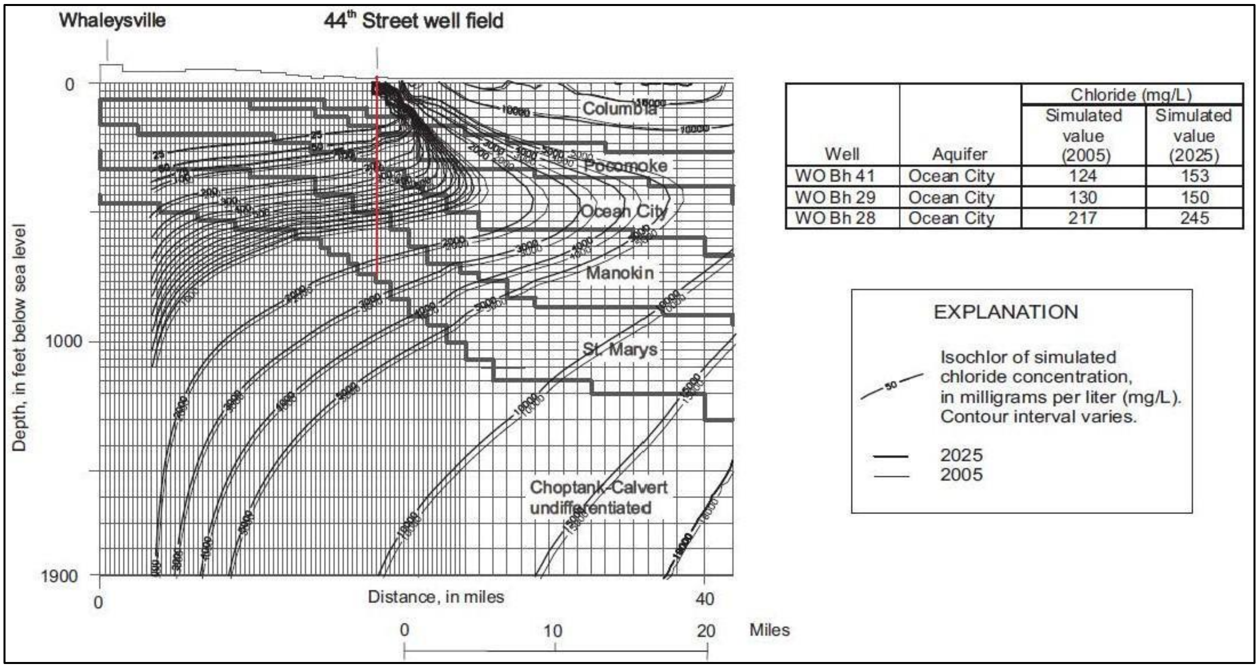
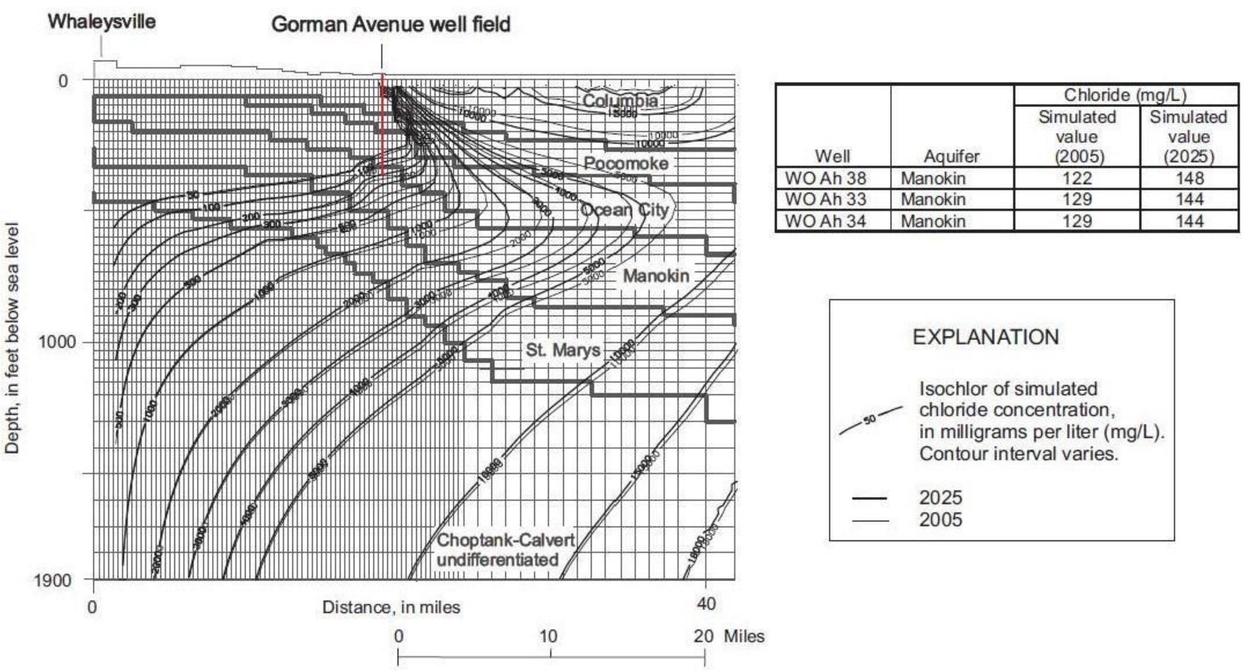


Figure 23 Simulated 1900 prepumping chloride concentrations in observation wells at the 15th Street cross-sectional model. Reproduced from Achmad and Bolton (2012), Fig 36.



Well	Aquifer	Chloride (mg/L) Simulated value (2005)	Simulated value (2025)
WO Bh 41	Ocean City	124	153
WO Bh 29	Ocean City	130	150
WO Bh 28	Ocean City	217	245

Figure 24. Simulated 1900 prepumping chloride concentrations in observation wells at the 44th Street cross-sectional model. Reproduced from Achmad and Bolton (2012), Fig. 37.



Well	Aquifer	Chloride (mg/L) Simulated value (2005)	Simulated value (2025)
WO Ah 38	Manokin	122	148
WO Ah 33	Manokin	129	144
WO Ah 34	Manokin	129	144

Figure 25. Simulated 1900 prepumping chloride concentrations in observation wells at Gorman Avenue cross-sectional model. Reproduced from Achmad and Bolton (2012), Fig. 38.

Sea Level Rise and Brackish Water Intrusion in Maryland

Jasechko et al. (2020) indicated that salt water intrusion is most likely to occur where water tables lie below sea level but can also arise from groundwater pumping in some coastal aquifers with water tables above sea level. They demonstrated that the majority of ~ 250, 000 observed groundwater levels lie below sea level along more than 15% of the contiguous coastline of the United States, including both shores of the Chesapeake Bay, except for the upper portion of the watershed. Where most or all well water elevations lie below sea level, excluding those in confined aquifers, they concluded that it may take decades for seawater to move inland, due to limited groundwater flow speeds as a function of the hydraulic conductivity of aquifers. If vulnerable aquifers can be identified in time, the worst impacts of seawater intrusion can potentially be avoided.

Ferguson et al. (2012) developed groundwater flow models that indicated that that coastal aquifers were more vulnerable to groundwater extraction than to predicted sea-level rise under a wide range of hydrogeologic conditions and population densities. Only aquifers with very low hydraulic gradients are more vulnerable to sea-level rise and these regions will generally have low topographic relief making them susceptible to inundation as well as lateral saltwater intrusion.

Few of the water supplies in Maryland have been impacted by brackish water intrusion. A vast number of Maryland’s surface water users rely on water bodies that are west of the fall line and distant from areas that could be impacted by sea level rise (e.g., Potomac River and WMA reservoirs, and Susquehanna River and Baltimore City reservoirs). Most of Maryland’s groundwater users take water from aquifers that are not impacted by saltwater intrusion, either in the Piedmont far from tidal waters or deep confined aquifers in the Coastal Plain protected by overlying, low permeability confining units.

In addition to the known areas of brackish water intrusion previously discussed, there are some other groundwater users within the coastal plain which rely on unconfined aquifers. Generally, Maryland’s unconfined aquifers are at a low risk of saltwater intrusion now; however, the portion of the unconfined aquifer that could be inundated by sea level rise could be at greater risk of having saltwater intrusion in the future.

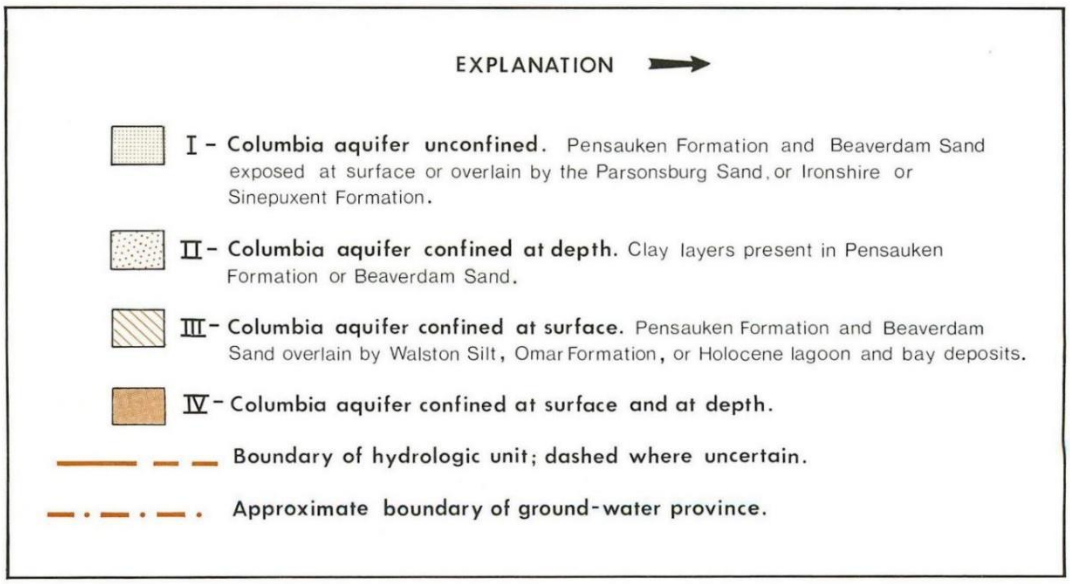
The Scientific and Technical Working Group of the Maryland Climate Change Commission (Boesch et al., 2013) updated Maryland’s previous (Boesch, Editor, 2008) sea level rise projections. The National Research Council’s (NRC) projections of global mean sea-level rise (SLR) were used as a starting point, with projections of relative sea-level rise in Maryland made through adjustments for the “fingerprint” effects of the land-ice contributions, as well as inclusion of the dynamic ocean contributions and the effects of vertical land movement. The adjusted contributions were then summed for the effects thermal expansion, land-ice loss, dynamic ocean effects, and vertical land movement (VLM). The results were then presented as Best, Low, and High projections of relative sea-level rise for Maryland for 2050 and 2100, Table 10. Both the low and high scenarios were considered unlikely.

Table 10. Maryland relative sea level rise, data from Scientific and Technical Working Group, Maryland Climate Change Commission, Boesch et al. (2013), p. 15.

Maryland	Thermal	Glaciers	Greenland	Antartica	Dynamic	VLM	Relative SLR	
Relative Sea Level Rise	m	m	m	m	m	m	m	ft
2050 best	0.10	0.05	0.03	0.09	0.09	0.075	0.4	1.4
2050 low	0.04	0.05	0.02	0.04	0.07	0.065	0.3	0.9
2050 high	0.19	0.06	0.05	0.16	0.10	0.085	0.7	2.1
2100 best	0.24	0.13	0.10	0.30	0.17	0.15	1.1	3.7
2100 low	0.10	0.12	0.08	0.10	0.13	0.13	0.7	2.1
2100 high	0.46	0.17	0.17	0.58	0.19	0.17	1.7	5.7

Figure 26 (and Table 11) is primarily a map of the Maryland portion of the Chesapeake Bay, showing the estimated sea level rise for 2050 (about 2 ft) and 2100 (about 4 ft). It shows little or no effect of sea level rise on the known areas where brackish water intrusion has occurred (Annapolis Neck/Mayo Peninsula, Kent Island, Baltimore Harbor and Ocean City). The area that will be most affected is the tidewater portion of southwest Dorchester County. Smaller areas will also be affected in the southwest portions of Wicomico and Somerset Counties, as well as upstream portions of the tidal creeks on the Eastern Shore. Most of the major population centers such as Cambridge, Centreville, Easton, and Princess Anne withdraw from confined aquifers for their public water supplies. The largest population center is the City of Salisbury which withdraws its water from the unconfined Salisbury Paleochannel. That aquifer, however, is in an area unlikely to be affected by sea level rise. Towns that also withdraw water from the unconfined portion of the Columbia aquifer are Hurlock, Vienna, Sharptown, Fruitland, Berlin, Briddletown, Mystic Harbor, and Ocean Pines. Vienna and Sharptown are along the Nanticoke River, which is the tributary most likely to be affected by sea level rise. Should brackish water reach those two water supplies, then the towns would have to consider drilling replacement wells far away from the Nanticoke River or to deeper confined aquifers.

Table 11. Hydrologic units for the Columbia aquifer. Reproduced from Bachman and Wilson (1984), p. 18.



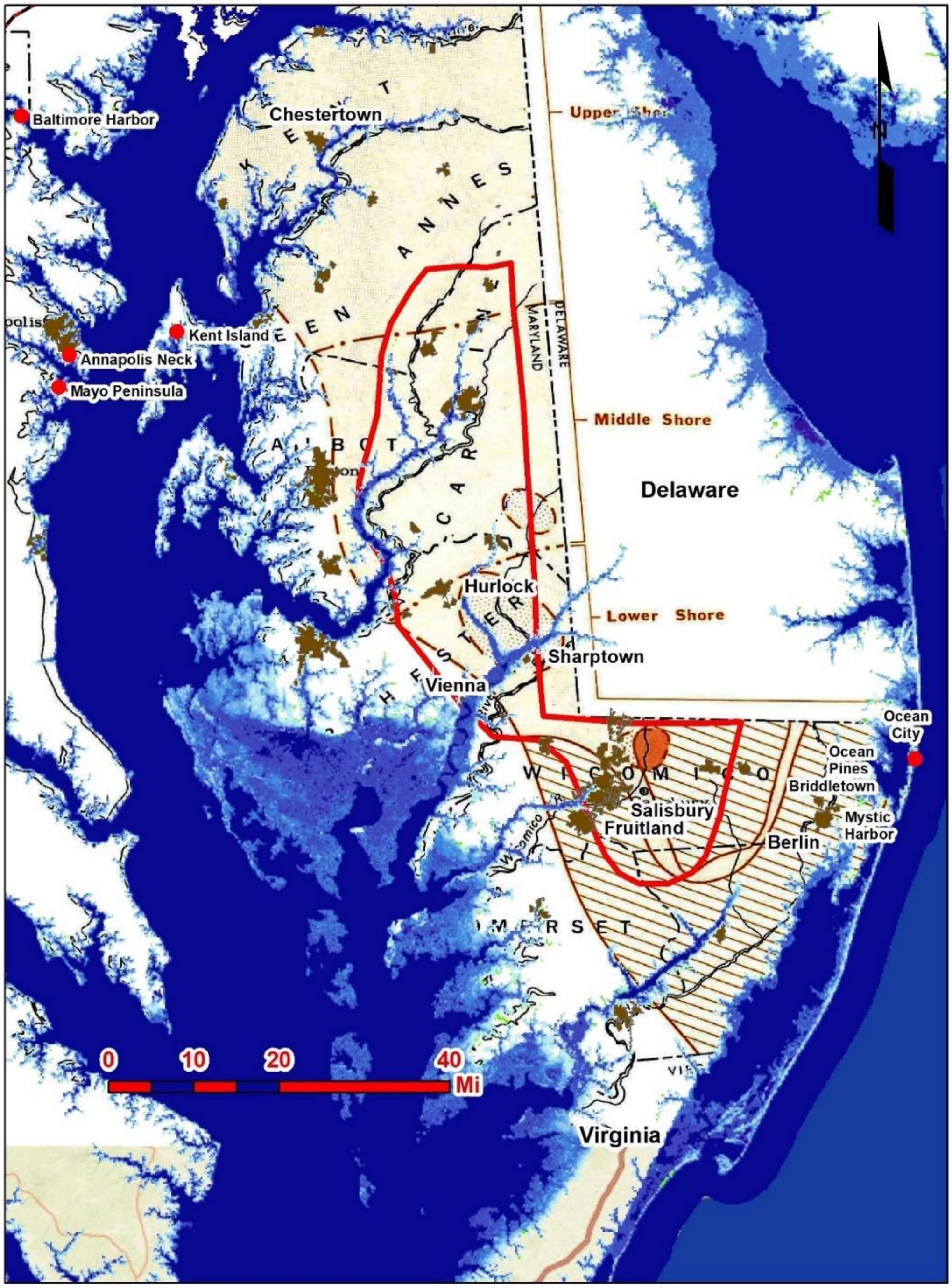


Figure 26. Map of primarily the Maryland portion of the Chesapeake Bay and the projected sea level rise for 2050 (about 2 ft) and 2100 (about 4 ft), data from NOAA Office for Coastal Management (coastal.info@noaa.gov) and the Columbia aquifer with the primary farm irrigation area (outlined in red). The hydrologic units for the aquifer are in Table 11.

The Effects of Climate Change on the Fractured Rock Aquifers of Central Maryland

Maryland includes much of the major Washington-Baltimore metropolitan region, where six million people live. Most of the metropolitan area is served by surface water from the Potomac River and associated reservoirs, and the Baltimore City reservoir system and, in an emergency, diversion from the Susquehanna River. There was a prolonged drought in the State during the period 1998–2002, culminating in (2001-2002) one of the three worst droughts on record, the others occurring in 1930–1932 and 1962–1969. The major surface water systems in the metropolitan area easily supplied customer demand, due to their large reservoir storage facilities. Some of the fastest growing suburban areas, however, were in the Piedmont and Blue Ridge areas, and supplied by small reservoirs and/or wells in fractured rock aquifers. Many of these small to medium size towns or cities, however, were required to institute voluntary or mandatory water restrictions. This was attributed to declining well yields caused by the drought; however, a study by Hammond (2004) indicated that initial predictions of the reliable yields of the public supply wells had been substantially overestimated.

Actions Taken During the Droughts of 1998-99 and 2001-02

On 7/29/1999, the Governor declared a Statewide drought emergency. At that time, it appears the Poolesville (Montgomery County) and other communities in Allegany, Calvert, Carroll, Cecil, Frederick Washington, and Wicomico counties had already imposed water restrictions, Frederick News Post on 7/30/1999. The Statewide restrictions were lifted 45 days later, after a period of high precipitation.

On April 5, 2002, the Governor declared a drought emergency for central Maryland to include Cecil, Carroll, Harford, Howard and Frederick counties, and the portions of Montgomery and Baltimore counties not served by either WSSC or were within the City of Baltimore service area.

The following is a status as of 12/13/2002 contained in the MDE-wsp record files:

Carroll County

Freedom District – No restrictions until Governor imposed water restrictions on central Maryland. More stringent restrictions imposed in October 2002 when reservoir levels were low.

Hampstead – Mandatory restrictions in March 2002 due to declining well water levels.

Manchester – Mandatory restrictions December 2001 due to declining well water levels and decreasing spring flow.

Mount Airy – Mandatory restrictions in June 2001 due to water demand exceeding well yields.

Taneytown – Mandatory restrictions in August 2001 due to declining well levels.

Westminster – Mandatory restrictions in December 2002 due to declining reservoir levels and problems maintain required flow-by.

Montgomery County

Poolesville – Voluntary restrictions March 2002. Well 6 reduced use due to declining water level and well 2 out of service due to a Groundwater Under the Direct Influence of Surface Water (GWUDI) evaluation.

Rockville – Voluntary restrictions in place February 2002 because of drought warning for central Maryland issued by State, but, had no drought related problems.

WSSC – No voluntary or mandatory restrictions imposed.

<u>Worcester County</u>
Berlin – Mandatory restrictions July 23, 2002, due to increased demand.
Ocean City – No restrictions or drought related problems.
Ocean Pines – Demand was up and well water levels declining, so the County was considering whether to impose water restrictions.

Information in a Frederick New Post article dated 4/24/2002 indicated that 7 of 10 water systems in Frederick County had more severe restrictions in place than those of the State. While not named, it is likely that these were the water systems for Myersville, Middletown, Emmitsburg, Thurmont, and either Point of Pocks, Walkersville, Woodsboro, or Mount Airy. The three which adhered to State's restrictions were the City of Frederick, Brunswick, and Frederick County Department of Utilities and Solid Waste Management (DUSWM). Not included in the MDE files are records from the Cecil, Harford, or Howard counties. It is possible that Aberdeen Proving Ground (APG) in Harford County had to impose water restrictions during the 2002 drought. Howard County appears to have been supplied by WSSC, the City of Baltimore PWS, or private wells.

Summary of Methods for Estimating and Monitoring Public Supply Well Yields in Fractured Rock Aquifers

The methods developed by Hammond (2018) and expanded upon by Hammond (2021) to estimate reliable drought yields of fractured rock wells consisted of: (1) extrapolating drawdown data from infinite acting radial or pseudo-radial flow (IARF) periods, or by fitting type curves of other conceptual models to the data. (2) The positions of transition zones in crystalline rocks or thin-bedded consolidated sandstone/limestone layers (reservoir rock units) were then used to determine available drawdowns in the wells. (3) Aquifer dewatering effects were detected by type-curve matching of step-test data or by breaks in the drawdown curves constructed from aquifer pumping tests. The predicted yields were confirmed by comparisons with operational water use and water-level data collected by water system personnel. The results were also compared to changes in regional groundwater levels to determine seasonal variations in well yields. Reliable estimates of drought yields are critical for effective design of production wells in fractured rock aquifers.

Additionally, long-term monitoring is needed to verify those estimates and provide evidence of any decline in yield due to changes in aquifer properties or mechanical failure of a well. Several systems developed methods to record well yields and water levels; however, Poolesville is the only one that has reported the results to MDE-wsp on a regular basis. It is likely that the MGS set up the monitoring and recording program for the town in about 1970, when the first wells for the water system were completed. It appears that the town continued the monitoring and recording system and started submitting the data to MDE as part of the Monthly Operating Report (MOR) in about 1997. Operational data from the Hammond (2021) investigation and other studies indicate that when a well is pumped continuously the maximum yields during wet periods may be two and one-half to three times greater than minimum drought yields. However, when pumped intermittently to meet demand, the ratio is likely closer to two to one. Once a well is placed in service, the estimated yield is best verified by the collection and analysis of the following daily operational well data: Pumpage (water use), hours pumped and, as a minimum, the water level at the end of the pumping drawdown cycle. Figure 27 is an example of a form MDE developed for the City of Taneytown to record operational data.

City of Taneytown Monthly Water Use Report Month: November Year: 2004

		Well 11 Mwbz 290-315 ft pump 349 ft 82 gpm csg 53 ft Tdepth 625 ft				Well 12 Mwbz 90-427 ft pump 205 ft ? gpm csg 56 ft Tdepth 590 ft				Well 13 Mwbz 325-580 ft pump 357 ft 120 gpm csg 165 ft Tdepth 580 ft				Well 14 Mwbz 394-601 ft pump 462 ft 130 gpm csg 61ft Tdepth 615(700) ft			
	R.F.																
Date	in.	hrs	gallons	gpm	level	hrs	gallons	gpm	level	hrs	gallons	gpm	level	hrs	gallons	gpm	level
1		16.0	78000	81.3		0.0	0	####		###	133000	138.5		16.0	103000	107.3	
2		16.5	73000	73.7		0	0	####		17	130000	131.3		17	93000	93.9	
3		12	66000	91.7		0	0	####		12	119000	165.3		12	98000	136.1	
4	1.3	14.5	74000	85.1		0	0	####		15	125000	143.7	102	15	93000	106.9	166
5		16	69000	71.9		0	0	####		16	129000	134.4		16	91000	94.8	
6		13	65000	83.3		0	0	####		13	129000	165.4		13	98000	125.6	
7		17	83000	81.4		0	0	####		17	139000	136.3		17	107000	104.9	
8		0	0	#####		12.5	120000	160.0		14	118000	145.7		14	90000	111.1	
9		0	0	#####		13	100000	128.2		13	105000	140.0		13	82000	109.3	
10		0	0	#####		13.5	100000	123.5		14	113000	139.5		14	88000	108.6	
11	0.4	0	0	#####		13	120000	153.8		14	118000	145.7		14	86000	106.2	
12	1.1	0	0	#####		15	100000	111.1		13	99000	126.9	95	13	79000	101.3	165
13		0	0	#####		13.5	110000	135.8		15	118000	131.1		15	90000	100.0	
14		0	0	#####		15	130000	144.4		14	121000	149.4		14	92000	113.6	
15		15	63000	70.0		0	0	####		15	122000	135.6		15	93000	103.3	
16		14.5	77000	88.5		0	0	####		15	120000	137.9		15	97000	111.5	
17		14	62000	73.8		0	0	####		14	123000	146.4		14	85000	101.2	
18		14.5	78000	89.7		0	0	####		15	117000	134.5	94	15	98000	112.6	165
19	0.1	14	66000	78.6		0	0	####		14	117000	139.3		14	86000	102.4	
20	0.2	15.5	81000	87.1		0	0	####		16	132000	141.9		16	104000	111.8	
21		17	82000	80.4		0	0	####		17	137000	134.3		17	105000	102.9	
22		0	0	#####		14	110000	131.0		14	115000	136.9		14	83000	98.8	
23	0.2	0	0	#####		14	110000	131.0		14	110000	131.0	95	14	90000	107.1	165
24	0.6	0	0	#####		14	110000	131.0		14	114000	135.7		14	86000	102.4	
25		0	0	#####		15	110000	122.2		15	118000	131.1		15	87000	96.7	
26		0	0	#####		12	110000	152.8		12	107000	148.6		12	77000	106.9	
27	0.5	0	0	#####		16.5	130000	131.3		17	140000	141.4		17	113000	114.1	
28		0	0	#####		16	130000	135.4		16	119000	124.0		16	94000	97.9	
29		0	73000	#####		0	0	####		14	124000	147.6		14	96000	114.3	
30	0.9	0	68000	#####		0	0	####		13	123000	157.7		13	93000	119.2	
31				#####				####				####				####	
TOT	5.3	209.5	1158000	XXX	XXX	197.0	1590000	XXX	XXX	###	3634000	XXX	XXX	###	2777000	XXX	XXX
AVG		7.0	38600	#####	###	6.6	53000	####	###	###	121133	141	97	14.4	92567	107	165
Measure water level and production data near (& before) end of pumping cycle																	

Figure 27. Example of monthly water use and water level monitoring report prepared for the City of Taneytown.

Potential Effects of Climate Change on Well Yields in Fractured Rock Aquifers

Once a reliable yield is established, then some means for estimating the effects of climate change on the well yields is needed. On a regional basis, well yields would vary with changes in aquifer recharge and groundwater storage. Studies have been conducted at scales from global, to North America, to northeast United States, and to the Potomac River basin describing the effects of climate change on aquifer recharge.

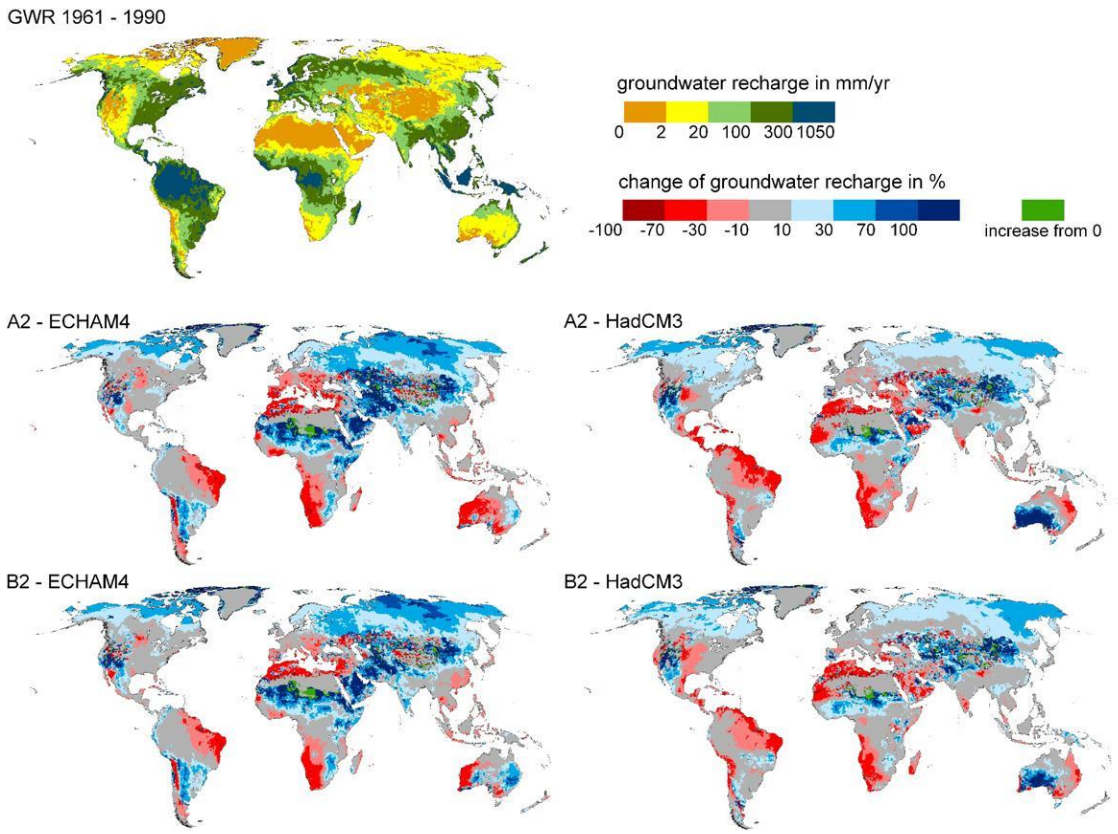


Figure 28. Impact of climate change on long-term average groundwater recharge GWR in the 2050s. Long-term average 1961–1990 groundwater recharge, in mm yr−1, and per cent changes between 1961–1990 and 2041–2070, as computed by WGHM applying four different climate change scenarios (climate scenarios computed by the climate models ECHAM4 and HadCM3, each interpreting the IPCC greenhouse gas emission scenarios A2 and B2). Reproduced from Döll (2009), Fig 1.

At the global scale, Döll (2009) indicated that the areas with the highest vulnerabilities to recharge due to climate change were the north African rim of the Mediterranean Sea, southwestern Africa, northeastern Brazil, and the central Andes, Figure 28. For most of the areas in the northern hemisphere the model results indicate that groundwater recharge is unlikely to decrease by more than 10% until the 2050s. In Maryland the changes in recharge range from -10% to +10%.

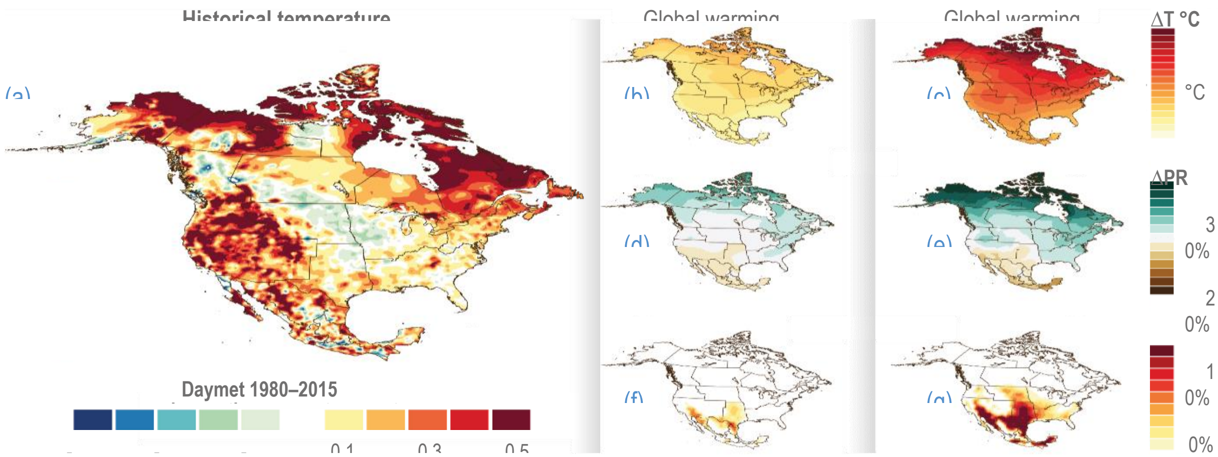


Figure 29. Observed and projected climate changes across North America. (A) Recent observations; (B) to (G) are from an ensemble of CMIP6 projections.
(A) Observed annual mean temperature trend over land for 1980–2015.
(B,C) Projected change in annual mean temperature over land relative to the 1986–2005 average, associated with 2°C or 4°C (3.6°F to 7.2°F) global warming.
(D,E) Like (B,C) but for projected percentage change in annual precipitation.
(F,G) Like (B,C) but for projected change in number of days per year with maximum temperature >40°C (‘TX40’). Reproduced from IPCC (2022), Fig. 14-2.

IPCC (2022) presented modeled values for the effects of climate change on temperature and precipitation on the North American continent, associated with 2°C to 4°C (3.6°F to 7.2°F) of global warming, Figure 29. The annual temperature has increased in recent decades in Maryland at a moderate rate. Pronounced warming across the Arctic and continental intensification of warming was projected with high confidence, while total precipitation was projected to increase across the northern half of North America with very high confidence. In Maryland, both the temperature and precipitation are projected to increase, while the number of days with a temperature >40°C (104°F) is projected to be nil.

Hayhoe et al. (2007) used statistical and dynamical downscaling methods and IPCC emission scenarios to predict future climate change across the northeast U.S. Future simulations were forced by the IPCC higher (A1fi - 970 ppm CO_2) and lower (B1 - 550 ppm CO_2) emissions scenarios, with the A1fi scenario representing a proxy for continuation of present-day economic growth and the B1 scenario a stabilization of CO_2 concentrations. The largest temperature increases by end-of-century (2070-2099) appear towards the northern part of the study area, while precipitation decreases in the northern and increases in the southern portions of the study area, Figure 30. Maryland is on the southern edge of the study area.

Rivard et al. (2008) constructed a hydrological/climate change model for a small (3.1 mi^2) watershed in Annapolis Valley, Nova Scotia, Canada which demonstrated that past and future recharge values are very similar throughout the year. Summer recharge, however, did show a modest annual decreasing trend of 0.02 in/yr or 0.6 in over 30 years. In a follow-on study of a much larger catchment (211 mi^2) in the Annapolis Valley, model runs by Rivard et al. (2014) projected an increase (14-45%) in annual recharge over the 2041–2070 period. On a seasonal basis, however, there was a significant decrease (17%) in recharge during the summer growing season (May-Oct) and a substantial increase during the winter, Jan-Mar (200%). The items not considered were the contribution of water taken from storage and the effects of water restrictions. When water demand is low during the non-growing season, recharge captured and retained in groundwater storage can then be used to supply summertime needs. Water restrictions can reduce summertime demand by about 25 to 35%, Hammond (2021), primarily due to the elimination of outdoor water use. Both are factors comparable to the reduced summertime recharge due to climate change in the Nova Scotia watershed.

Ascott et al (2019) hypothesized that vertical hydraulic conductivity (VKD) exerted a significant additional control on borehole yields under climate change and to demonstrate that they developed a simple two-layered radial groundwater flow model of an idealized pumping borehole in the fractured Chalk aquifer of south-east England. Twenty climate scenarios and six constant pumping rates were applied to 11 VKD profiles for the period 1962–2014, and borehole yields were estimated based on derived lowest pumping water levels during key drought years. It was demonstrated that the hydraulic properties of the aquifer were more effective than changes in climate in controlling lowest pumping groundwater levels when pumping rates were less than 1651 gpm (9000 m^3/d), and that both were significant at rates greater than or equal to 1651 gpm, yields that only may be achieved in the carbonate rock aquifers of Maryland, although it is unknown if any wells have produced this amount.

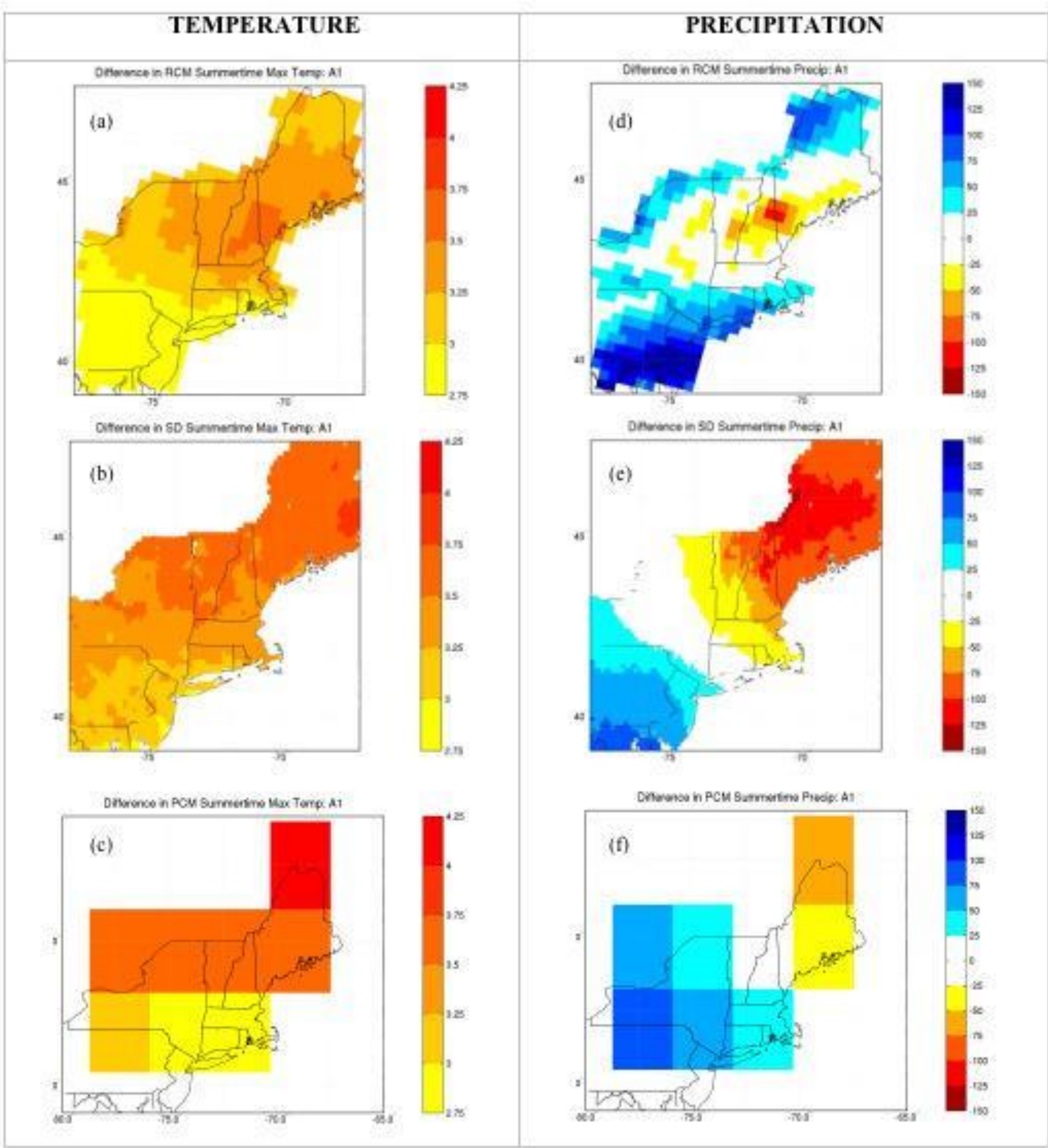


Figure 30. Projected changes in daily maximum temperatures (K) and total precipitation (mm) assimilated by (a-d) MM5-based regional modeling, (b-e) statistical downscaling and (c-f) PCM for the 2090s relative to the 1990s. Note: MM5 (PSU-NCAR Mesoscale Model) PCM (USDOE- NCAR Paralled Climate Model). Reproduced from Hayhoe et al. (2007), Fig. 2.

Table 12 contains Potomac River basin-wide averages of annual precipitation, evapotranspiration, stormflow, and baseflow for the base scenario and 18 climate scenarios, Ahmed et al. (2013). The calculations were restricted to areas of the upper portion of the Potomac watershed, upstream of the USGS gage on the Potomac River at Little Falls near Washington, D.C. The average precipitation increases in the Potomac River basin in nine out of the 18 climate change scenarios, and evapotranspiration increases in all climate change scenarios due to elevated temperatures. The average annual baseflow decreases (by 3% to 33%) within the basin in 16 out of the 18 scenarios. For those seven scenarios where precipitation increases, as suggested by most other studies of northeast USA, the precipitation then largely cancels out losses due to evapotranspiration, with average baseflow or effective recharge changing by 88% to 104% in 2040 due to climate change relative to the base period of 1988-1999. In addition, storm flows change by 93% to 120%, while total stream flow changes by 90% to 111%, indicating that climate change will have slightly less impact on the reservoirs and simple intakes of the small to medium sized communities of central and western Maryland. A review of Washington DC annual precipitation (dcaprecip) and temperature (dcatemps) data from 1871 to 2023 at the present Reagan National Airport, suggest that the number of applicable scenarios can be reduced.

. Figure 31 is a graph of the temperature indicating there is a substantial increase in the temperature (5.5°F or 3.1°C) over the period of record. From the linear equation for the temperature data the R^2 value is 0.6839. A regression analysis produced a P-value of 0.0122. The relatively high R^2 and low P-value indicates that the solution explains much of the variation in the data and is statistically significant. The 2nd order polynomial also provides a good fit to\the data (R^2 = 0.689), but the P-value requires a special analysis program that is not available.-The ICPRB models project the impacts of climate change from the base period of 1988-1999 to 2040. Projecting the dcatemps data to 2040 produces increases of 0.9 and 1.1°C for the linear and 2nd order polynomial solutions, respectively. While the dcatemps data may not be representative of the entire Potomac River basin upstream of Little Falls, the rate of change may be similar to the regional trend. To address the heat island effects at Reagan Airport, the Maryland State temperature data, complied from 11 stations from the Eastern Shore to Garrett County, NOAA NCEI (2022, 2024), were reviewed, which indicated that the temperature in that data set when projected from 1900 to 2020 is 2.5°F, Fig 32, or the same as that due to climate change in Washington D.C. Projecting the Maryland Statewide data to 2040 produces increases of 0.6 and 1.3°C for the linear and 2nd order polynomial solutions, respectively While the absolute projected temperature in Washington D.C. would reflect both climate change and heat island effects, the rate of change is similar to the Maryland Statewide data and can be used to approximate the increase in temperature due to climate change

In the case of the dcaprecip rainfall data, Fig 33, both the linear and second order polynomial equations produce the only solutions extrapolated to 2040 that are within the range of prediction of the ICPRB models, the R^2 results are very low (0.0387 and 0.0065) and a regression analysis produced a high P-value (0.3213). This indicates that the result explains little of the variation in the data and is not statistically significant. The same results were obtained for the Maryland Statewide precipitation data, Fig. 34, with low R^2 values of 0.0445 and 0.0528, although the P-value is 0.017.

Table 12. Basin-wide mean annual water budget for the base scenario and for the 18 climate change scenarios. Reproduced from Ahmed et al. (2013). Tables 3-1, 3-2 and 5-1.

Scenario	Temperature change	Precipitation	Evapo transpiration	Stormflow	Baseflow	Total stream flow
	(°C)	(inches)	(inches)	(inches)	(inches)	(inches)
Base	0.00	42.2	27.3	6.4	8.6	15.0
B_A1B	1.2	42.2	29.0	5.9	7.5	13.4
B_A2	0.8	41.7	28.5	5.8	7.5	13.3
B_B1	0.7	45.0	28.5	7.7	8.9	16.6
C3.0_A1B	1.3	44.0	29.2	6.7	8.2	14.9
C3.0_A2	1.4	43.7	29.2	6.5	8.1	14.6
C3.0_B1	1.1	41.0	28.5	5.3	7.3	12.6
C3.5_A1B	1.6	38.2	28.9	4.0	5.7	9.7
C3.5_A2	1.6	39.6	28.7	4.7	6.4	11.1
C3.5_B1	0.9	41.3	28.7	5.6	7.2	12.8
I_A1B	2.3	38.9	29.5	3.8	5.9	9.7
I_A2	2.1	39.1	29.2	4.1	6.0	10.1
I_B1	1.8	38.6	28.9	4.0	5.9	9.9
M_A1B	2.2	42.1	29.9	5.3	7.1	12.4
M_A2	1.8	39.8	29.0	4.5	6.5	11.0
M_B1	1.6	42.8	29.4	6.0	7.5	13.5
N_A1B	1.7	45.5	30.2	7.0	8.3	15.3
N_A2	1.6	46.1	30.2	7.4	8.6	15.9
N_B1	1.2	45.1	29.5	7.3	8.3	15.6
Average	1.5	41.9	29.2	5.6	7.3	12.9

Scenario	Precipitation	Evapo transpiration	Stormflow	Baseflow	Total stream flow	Rank
	(percent)	(percent)	(percent)	(percent)	(percent)	
Base						
B_A1B	100%	106%	93%	87%	89%	8
B_A2	99%	104%	90%	88%	89%	9
B_B1	107%	105%	120%	104%	111%	1
C3.0_A1B	104%	107%	104%	96%	99%	5
C3.0_A2	103%	107%	102%	94%	98%	6
C3.0_B1	97%	105%	83%	85%	84%	11
C3.5_A1B	91%	106%	63%	66%	65%	17
C3.5_A2	94%	105%	74%	75%	74%	13
C3.5_B1	98%	105%	87%	84%	86%	10
I_A1B	92%	108%	59%	68%	65%	18
I_A2	93%	107%	64%	70%	67%	15
I_B1	91%	106%	62%	69%	66%	16
M_A1B	100%	110%	83%	83%	83%	12
M_A2	94%	106%	70%	76%	73%	14
M_B1	101%	108%	93%	88%	90%	7
N_A1B	108%	111%	109%	97%	102%	4
N_A2	109%	111%	115%	100%	106%	2
N_B1	107%	108%	113%	97%	104%	3
Average	99%	107%	88%	85%	86%	

GCM Acronym	GCM Abbreviation	Institution/Model	Country
NCAR-CCSM3_0	N	National Center for Atmospheric Research	USA
BCC-BCM2.0	B	Bjerknes Centre for Climate Research	Norway
CSIRO-Mk3.0	C3.0	Commonwealth Scientific and Industrial Research Organisation	Australia
CSIRO-Mk3.5	C3.5	Commonwealth Scientific and Industrial Research Organisation	Australia
INM-CM3.0	I	Institute for Numerical Mathematics	Russia
MIROC3.2(medres)	M	National Institute for Environmental Studies	Japan

Emission Scenario Acronym	Emission Scenario Description
A2	High population growth, slow economic development and slow technological change
A1B	Very rapid economic growth and technological change, population peak mid-century, balance of energy sources
B1	Similar to A1B, but change toward service and information economy

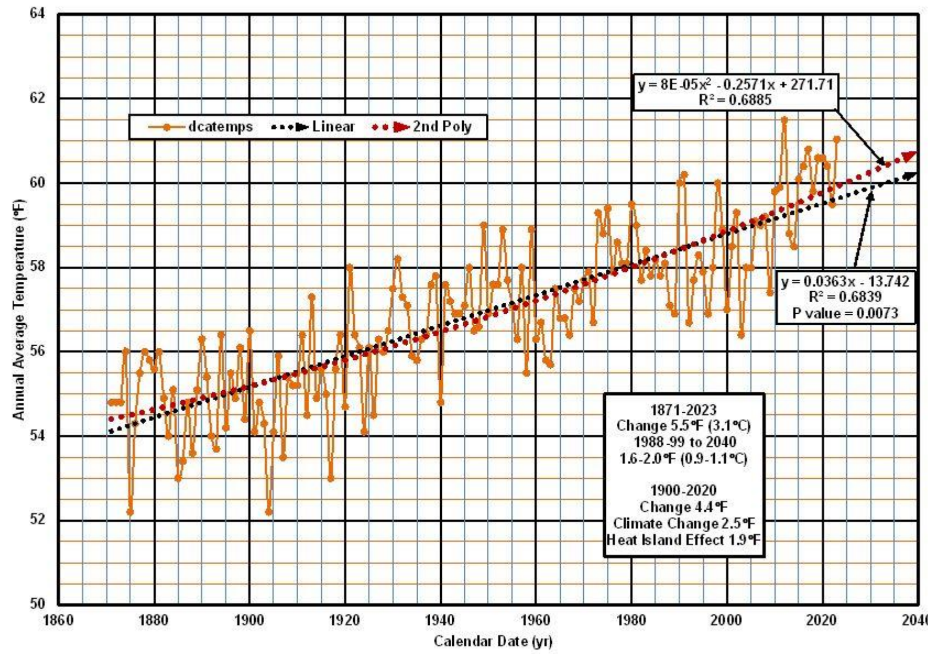


Figure 31. Annual average temperature (dcatemps) at the Reagan National Airport from 1871 to 2023, with data projected to 2040.

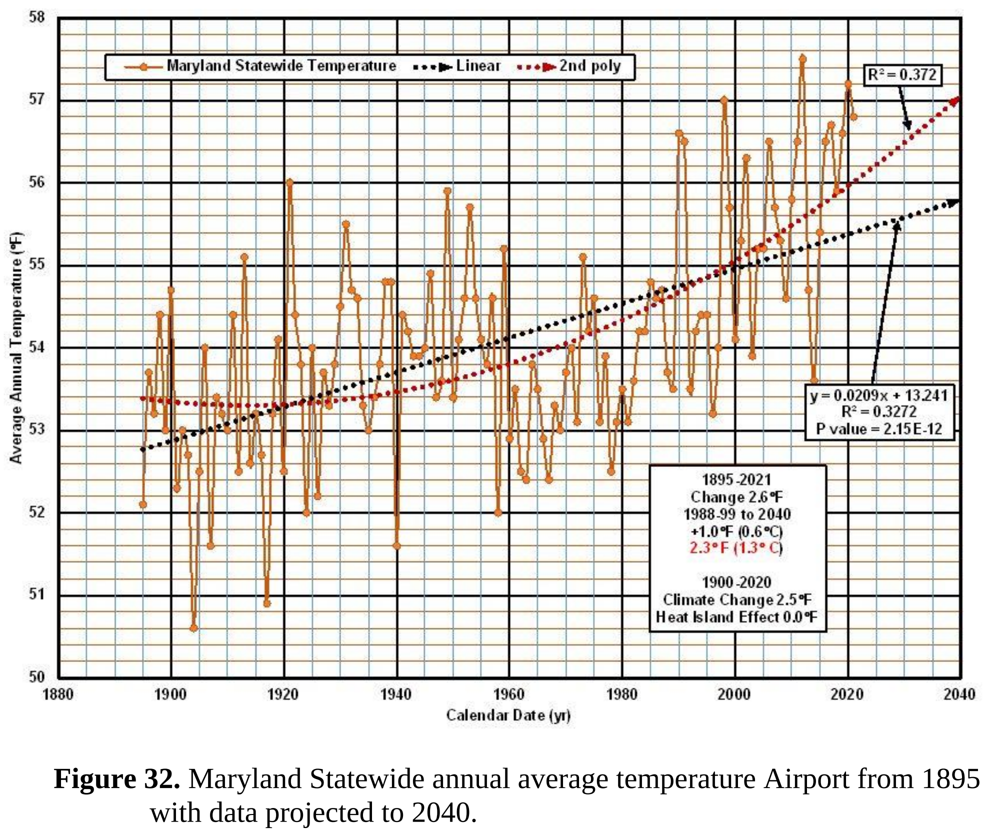


Figure 32. Maryland Statewide annual average temperature Airport from 1895 to 2021, with data projected to 2040.

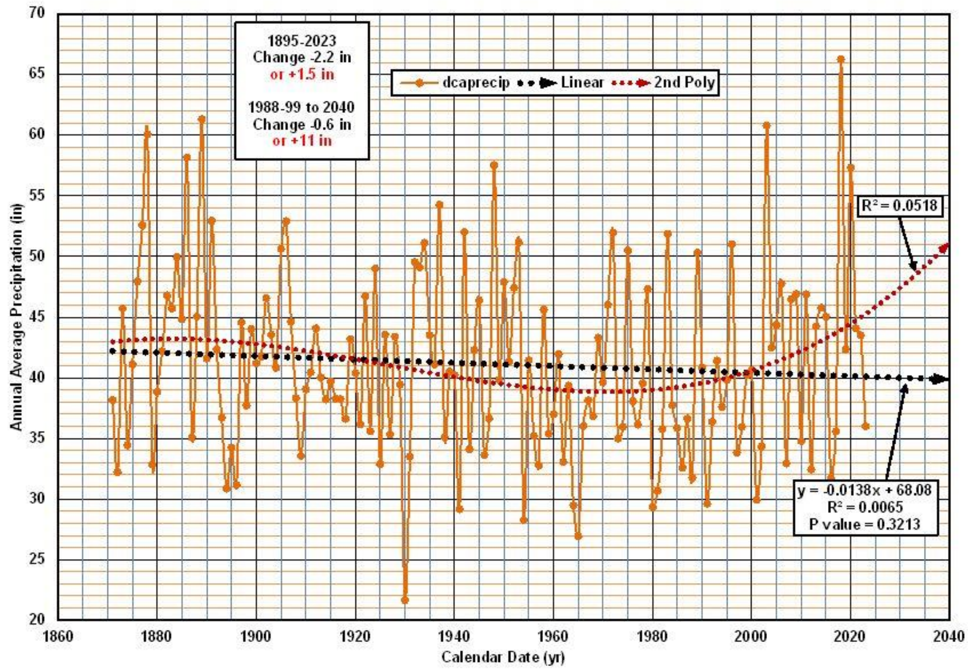


Figure 33. Annual average precipitation (dcaprecip) at the Reagan National Airport from 1871 to 2023, with data projected to 2040.

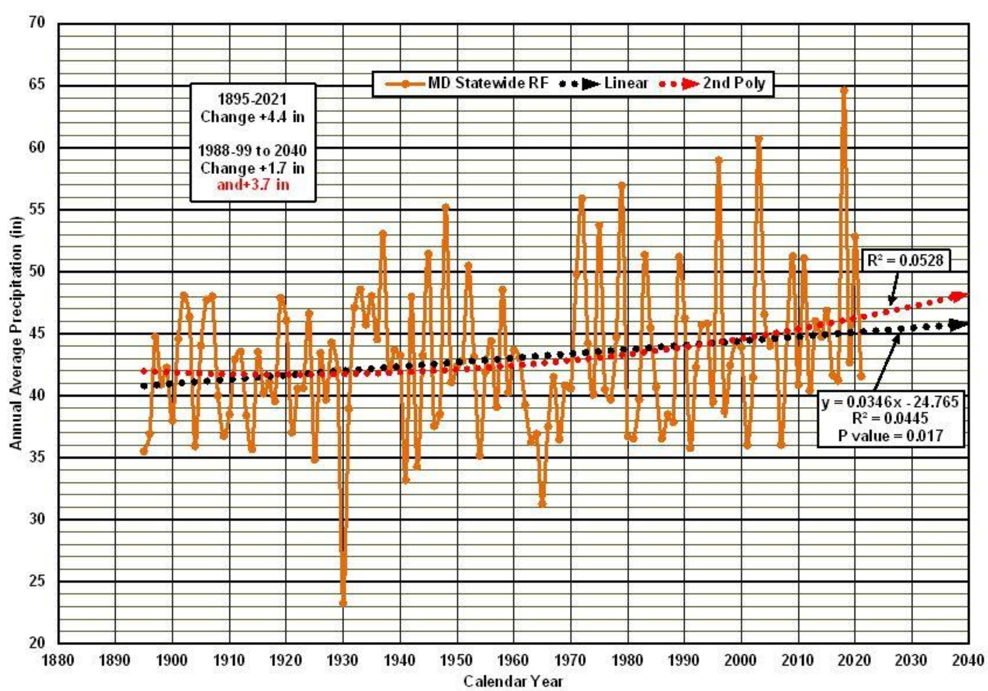


Figure 34. Maryland Statewide annual average precipitation from 1895 to 2021, with data projected to 2040.

Table 13. Basin-wide mean monthly inflow to groundwater storage (recharge) for the 18 climate change scenarios (inches and percentage of base). Reproduced from Ahmed et al. (2013), Table 5-2.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total annual
Base	1.31	1.28	1.69	0.67	0.81	0.42	0.44	0.34	0.44	0.46	0.70	0.90	9.46
B_A1B	1.21	0.86	1.75	0.65	0.83	0.47	0.33	0.34	0.36	0.38	0.51	0.72	8.41
	92%	*68%*	*103%*	*96%*	*103%*	*111%*	*75%*	*100%*	*82%*	*83%*	*73%*	*80%*	89%
B_A2	1.23	0.96	1.73	0.58	0.77	0.40	0.42	0.34	0.33	0.39	0.54	0.81	8.49
	94%	*75%*	*102%*	*87%*	*95%*	*94%*	*95%*	*98%*	*75%*	*84%*	*77%*	*90%*	90%
B_B1	1.74	1.11	1.87	0.53	0.80	0.50	0.45	0.41	0.35	0.43	0.60	1.05	9.84
	133%	87%	111%	79%	99%	117%	103%	119%	79%	94%	86%	117%	104%
C3.0_A1B	1.35	1.19	1.59	0.71	0.72	0.43	0.35	0.27	0.50	0.34	0.62	1.15	9.19
	103%	93%	94%	105%	89%	101%	79%	78%	114%	73%	89%	128%	97%
C3.0_A2	1.25	1.19	1.69	0.65	0.83	0.40	0.36	0.33	0.31	0.34	0.66	1.01	9.03
	95%	93%	100%	96%	103%	95%	83%	96%	71%	74%	96%	113%	95%
C3.0_B1	1.15	0.99	1.36	0.68	0.77	0.42	0.36	0.27	0.32	0.37	0.61	0.91	8.22
	88%	78%	80%	100%	95%	99%	82%	79%	74%	81%	88%	101%	87%
C3.5_A1B	1.27	0.92	1.22	0.55	0.56	0.38	0.31	0.28	0.23	0.13	0.33	0.68	6.87
	97%	72%	72%	81%	69%	89%	70%	82%	52%	29%	47%	76%	73%
C3.5_A2	1.06	0.94	1.36	0.63	0.59	0.31	0.26	0.22	0.34	0.25	0.46	0.56	6.99
	81%	74%	80%	94%	73%	74%	59%	65%	77%	55%	66%	62%	74%
C3.5_B1	1.27	0.96	1.16	0.57	0.63	0.34	0.28	0.17	0.37	0.26	0.32	0.56	6.90
	97%	76%	68%	85%	78%	81%	64%	50%	84%	55%	47%	62%	73%
I_A1B	1.43	0.98	1.36	0.58	0.72	0.36	0.27	0.30	0.29	0.36	0.53	0.94	8.12
	109%	77%	80%	86%	89%	85%	61%	86%	66%	79%	77%	104%	86%
I_A2	1.17	1.00	1.25	0.63	0.71	0.32	0.31	0.22	0.27	0.31	0.51	0.76	7.46
	89%	79%	74%	94%	88%	76%	71%	64%	61%	67%	73%	84%	79%
I_B1	1.33	0.99	1.46	0.71	0.86	0.41	0.39	0.26	0.28	0.34	0.60	0.91	8.53
	101%	78%	86%	106%	106%	96%	88%	75%	63%	74%	87%	101%	90%
M_A1B	1.29	1.09	1.69	0.63	0.72	0.41	0.46	0.39	0.50	0.41	0.69	1.04	9.32
	99%	85%	100%	93%	90%	98%	105%	112%	113%	89%	99%	116%	99%
M_A2	1.34	1.14	1.64	0.60	0.80	0.42	0.47	0.40	0.55	0.48	0.75	0.99	9.56
	102%	89%	97%	89%	99%	98%	106%	116%	124%	104%	107%	111%	101%
M_B1	1.24	1.05	1.70	0.60	0.77	0.43	0.48	0.38	0.47	0.47	0.78	0.93	9.31
	94%	83%	101%	90%	95%	101%	110%	110%	108%	103%	112%	104%	98%
N_A1B	1.29	1.09	1.69	0.63	0.72	0.41	0.46	0.39	0.50	0.41	0.69	1.04	9.32
	99%	85%	100%	93%	90%	98%	105%	112%	113%	89%	99%	116%	99%
N_A2	1.34	1.14	1.64	0.60	0.80	0.42	0.47	0.40	0.55	0.48	0.75	0.99	9.56
	102%	89%	97%	89%	99%	98%	106%	116%	124%	104%	107%	111%	101%
N_B1	1.24	1.05	1.70	0.60	0.77	0.43	0.48	0.38	0.47	0.47	0.78	0.93	9.31
	94%	83%	101%	90%	95%	101%	110%	110%	108%	103%	112%	104%	98%

While the dcaprecip data is not useful, the dcatemps data might help narrow the number of climate change scenarios, by selecting those near the projected increase in 2040 of 0.9-1.1°C. There are seven ICPRB scenarios between increases of 0.7°C and 1.3°C (to account for potential error and include the Maryland Statewide results) from the base period (1988-1999) to 2040., which are B_A1B, B_A2, B_B1, C3.0_A1B, C3.0_B1, C3.5_B1, and N_B1, which have 87%, 88%, 104% 96%, 85%, 84%, and 97%, respectively (average of 91.6%) of the average baseflow for the base period (8.6 in/yr), This indicates that the average annual baseflow in the study area will be reduced by about 0.7 in/yr. Since climate change will cause a multi decade stress of the groundwater system, then the baseflow in any year would be reduced by that amount, including any drought. For example, baseflow analyses have been calculated by MDE for two watersheds in the in the Potomac River basin, Monocacy River at Jug Bridge (gage # 01643000) in Frederick County and Seneca Creek at Dawsonville (gage # 01645000) in Montgomery County. During the period of record (1930-2021) at the Monocacy River gage, the average baseflow is 8.8 in/yr, the record low year (1-in-92 yr return) was 1931 (2.9 in.), the second lowest year (1-in-46 yr return) was 2002 (4.3 in/yr). Subtracting 0.7 in from the 1-in-10 yr drought (1963) baseflow of 5.0 in/yr equals 4.3 in/yr (14% decline) indicating that climate change could cause a 50-yr drought to occur at a 10-yr interval. Similar results were obtained with the data from the Seneca Creek gage. During the period of record (1931-2021) at the Seneca Creek gage, the average baseflow is 10.5 in/yr, the record low year (1-in-91 yr return) was 1931 (2.6 in.), and the second lowest year (1-in-46 yr return) was 1959 (5.0 in/yr). Subtracting 0.9 in from the 1-in-10 yr drought (1981) baseflow of 5.7 in/yr equals 4.8 in/yr (16% decline), again indicating that climate change could cause a 50-yr drought to occur at a 10-yr interval. Furthermore, Table 13 indicated that during the peak demand months of July and August, baseflow could be changed by an average of +11% to -43% (-11% average) relative to the base period.

Hammond (2021) described a review that was completed by MDE of production and monitoring records collected during the 1998-2002 drought from 97 wells and 2 springs of municipal purveyors and a few golf courses in the fractured rock areas of central Maryland. That study indicated that the average maximum drought production was only 54% of the estimated yields using the techniques then in common use, but 83% of the estimates made using the methods developed in the Hammond (2018) study. This suggests that errors in estimating the reliable yields of public supply fractured rock wells may have as great or greater effect than those caused by climate change.

Most of the previously discussed studies indicate that climate change may have limited impacts on the fractured rock aquifers of Maryland. Given the large uncertainty with modelling future recharge, Smerdon (2017) suggested that the focus on water management, monitoring and future modelling efforts should be placed on the next 10–20 years rather than the next 50–100 years typically used for climate models. Schultz et al. (2005) made estimates of annual baseflow (effective recharge) at four gaged sub-basins within or near the Monocacy River/Catoctin Creek watersheds. Seasonal groundwater availability was then estimated using seasonal water budgets and incorporating the effects of changes in aquifer storage. Summertime water availability was established by using the sum of the beginning summer storage and summer recharge. The estimates in that study did not apply in situations where ground water withdrawals resulted in zero stream flow. The time series for the seasonal water budgets was from October 1959 to September 2002 for the four sub-basins in the study. Median and mean recession coefficients for the four sub-basins were in the range of 33 to 87 days, indicating relatively poor storage capacities for the fractured bedrock aquifers, especially in the upper Monocacy and Catoctin Creek sub-basins. Uncertainties for the dry year annual recharge estimates were roughly ± 50%.

Table 14. Seasonal and annual water budget predictions Monocacy River and Catoctin Creek basins. Reproduced from Schultz et al. (2005), Table 15.

Seasonal water budget predictions of summer water availability, V_{Q3} (gpd/acre)				
Station	**2-year V_{Q3} (gpd/acre)**	**10-year V_{Q3} (gpd/acre)**	**20-year V_{Q3} (gpd/acre)**	**2001 Q3 GW Withdrawal Estimate (gpd/acre)**
Catoctin Creek (01637500)	**210**	**65**	**60**	**24**
Upper Monocacy (01639000)	**120**	**42**	**30**	**15**
Big Pipe Creek (01639500)	**460**	**190**	**150**	**16**
Bennett Creek (01643500)	**420**	**220**	**160**	**6**
Annual water budget predictions of annual recharge (gpd/acre)				
Station	**2-year 365-day baseflow (gpd/acre)**	**10-year 365-day baseflow (gpd/acre)**	**20-year 365-day baseflow (gpd/acre)**	**2001 Q3 GW Withdrawal Estimate (gpd/acre)**
Catoctin Creek (01637500)	**630**	**400**	**350**	**24**
Upper Monocacy (01639000)	**410**	**270**	**230**	**15**
Big Pipe Creek (01639500)	**620**	**400**	**350**	**16**
Bennett Creek (01643500)	**640**	**440**	**390**	**6**

Water availability predictions from the annual and the seasonal water budget approaches differed significantly, Table 14. Predictions of annual recharge in dry years (20-yr return), ranged from 350 gpd/acre in the Bennett Creek sub-basin to 230 gpd/acre for the upper Monocacy sub-basin. However, predictions of dry-year summer availability (20-yr V_{Q3}) ranged from 160 gpd/acre for the Bennett Creek sub-basin to only 30 gpd/acre for the upper Monocacy River sub-basin. The dry year summer availability prediction for the Catoctin Creek sub-basin was also extremely low, only 60 gpd/acre. The availability predictions were close to ground water withdrawals in the year 2001, estimated to be 15 and 24 gpd/acre for the upper Monocacy and Catoctin sub-basins, respectively. During the drought year, 2002, the Town of Middletown in the Catoctin Creek sub-basin experienced significant problems with its system of public supply wells and reported that streams in the area were dry or very low.

The seasonal water budget approach, a simple measure of water availability, Table 14, is defined by the volume of water stored in the upper portion of the sub-basin aquifer at the beginning of summer plus the volume provided by summer recharge. In the seasonal water budget analysis, sub-basin precipitation, stream baseflow, aquifer recharge, total evapotranspiration, and other water budget components were computed for every quarter during the period from 1960 through 2002, for the four sub-basins in the study area. A measure of the quantity of water available in the summertime, VQ3, of an average year was defined as the sum of beginning-of-summer aquifer storage (above the zero-stream discharge level) and summer recharge. Table 15 indicates S_{Q3} is 25 to 70% of R_{net3} suggesting that groundwater storage is a significant component of the amount of groundwater available during the summer quarter.

Table 15. Average Seasonal Water Budgets for Four Gaged Sub-Basins for Time Period, 1960 – 2002 (inches per quarter). Data from Schultz et al. (2005). Table 12.

Stream/Period	Precip	^{q}SF	^{q}BF	ET	^{R}net	ΔS	S	W	^{R}Xdry	Yr
Catoctin (01637500)										
Q1	9.9	1.9	4.4	2.8	5.2	0.7	0.7	< 0.05		
Q2	11.7	1.3	3.7	7.7	2.7	-1.1	1.4	< 0.05		
Q3	11.2	0.6	0.7	10.0	0.6	-0.1	0.3	< 0.05		
Q4	9.8	1.0	1.8	6.4	2.4	0.5	0.2	< 0.05		
Annual	42.5	4.8	10.7	26.9	10.8	0.0		0.1	4.2	2002
Bridgeport (01639000)										
Q1	10.0	4.5	2.9	2.3	3.1	0.2	0.3	< 0.05		
Q2	12.0	2.5	1.7	8.2	1.3	-0.4	0.5	< 0.05		
Q3	11.5	1.0	0.4	10.1	0.4	0.0	0.1	< 0.05		
Q4	9.9	2.2	1.2	6.2	1.5	0.2	0.1	< 0.05		
Annual	43.4	10.3	6.2	26.8	6.3	0.0		0.1	3.0	1954
Big Pipe (01639500)										
Q1	9.7	2.2	3.6	3.4	4.1	0.5	1.0	< 0.05		
Q2	11.4	1.3	3.0	8.0	2.1	-0.9	1.5	< 0.05		
Q3	11.4	0.8	1.2	9.5	1.1	-0.2	0.6	< 0.05		
Q4	9.8	1.1	1.9	6.2	2.5	0.5	0.4	< 0.05		
Annual	42.3	5.4	9.7	27.1	9.7	0.0		0.1	4.1	2002
Bennett (01643500)										
Q1	9.9	1.7	3.7	3.9	4.3	0.6	1.1	< 0.05		
Q2	11.8	1.4	3.3	8.1	2.3	-1.0	1.7	< 0.05		
Q3	11.6	0.8	1.2	9.8	1.0	-0.2	0.7	< 0.05		
Q4	10.4	1.0	2.0	6.7	2.6	0.6	0.5	< 0.05		
Annual	43.8	4.9	10.2	28.6	10.3	0.0		0.1	4.3	2002

Hammond (2022) estimated that the baseflow during 2002 in the Hollow Creek WHPA (Drainage area = 3.14 mi^2), near Middletown, was 623,000 gpd avg, or 4.2 in/yr, while withdrawals in the WHPA from the Middletown main well field and springs were 85% of that value, or 536,000 gpd avg, and the watershed above US Route 40 was completely dry. Water use was approximately equally distributed throughout the year, primarily due to the imposition of water restrictions. These data suggested that the substantial, potential, sustained natural drought flows in Hollow Creek are likely due to high recharge, ground water storage and stream infiltration within the basin.

On August 20, 2002, the flow in Woodville Branch (D.A. 6.6 mi2), from which Mount Airy withdraws its primary groundwater supply, was about 50 gpm (0.017 cfsm) (cubic feet per square mile), Hammond (2022). The withdrawal from the main well field (wells 1-4) was 403,100 gpd avg in 2002, which, with an estimated drainage area of 760 acres (1.2 mi^2), is the equivalent effective recharge of 530 gpd avg/ac (7.1 in/yr). That value was about 65% greater than the baseflow measured at the nearby Bennett Creek gage (4.3 in/yr). This would indicate that the natural flows in the spring-fed Woodville Branch watershed are enhanced by increased recharge, aquifer storage capacity, and stream infiltration.

In the case of the spring-fed Hollow Creek and Woodville Branch watersheds, the data indicates that, under natural conditions, they are major sources of water during low flow periods in Catoctin Creek and Linganore Creek, respectively.

In the case of the Poolesville public water supply, the use was 395,000 gpd avg in 2002. From an estimated drainage area of 1813 acres (2.83 mi^2), the use was the equivalent of 218 gpd avg/ac (about 2.9 in/yr) or 69% of the average baseflow at the Monocacy River @ Bridgeport gage. The distance from Poolesville to the gage station is 39 miles. The weather and different hydraulic characteristics between the two sites might explain the difference in the two effective recharge rates during the drought of 2002.

The water use and effective recharge rates at Middletown, Mount Airy and Poolesville more closely match the average of the representative gage sites and are much higher that the V_{Q3} summer water availability rates contained in the Schultz et al. (2005) study. These results can only be consistent if there is a high variability in the recharge and hydraulic characteristics within each watershed. In addition, the Schultz et al. (2005) model assumes that withdrawals are the sum of available recharge and storage, which would be much higher during the winter months (Q1, Jan-Mar) than in the summer months (Q3, Jul-Sep). However, water use by municipal water suppliers is much lower during the winter and higher during the summer due to outdoor water use. In the case of domestic users, much of the water withdrawn from their wells is returned to the aquifer through septic field recharge. This suggests that more water is available for use from the fractured rock aquifers than indicated in the Schultz et al. (2005) study. One additional factor is that the Schultz et al. (2005) study assumed that streams do not go dry. Of the three municipal sites, only Hollow Creek (Middletown) was observed to go dry during the drought of 2002, although the flows in the other two watersheds were severely reduced. From these results, it is best to monitor the individual water system yields instead of measuring baseflow on a watershed basis to determine the effects of climate change on public groundwater supplies in the fractured areas of the State.

Effects of Climate Change on Yields of Domestic Wells in the Fractured Rock Areas of Central Maryland

Nutter and Otton (1969) published the first comprehensive study of groundwater resources in the Maryland Piedmont. The following previous studies were reviewed by Nutter and Otton (1969): The Ground-Water Resources of the Piedmont in The Water Resources of Baltimore and Harford Counties (Dingman, Ferguson and Meyer, 1956); The Ground Water Resources in The Water Resources of Carroll and Frederick Counties (Meyer and Beall, 1958); The Ground-Water Resources in The Water Resources of Howard and Montgomery Counties (Dingman and Meyer, 1954); Water Resources of the Baltimore Area, Maryland (Otton, Martin, and Durum, 1964); and Records of Wells and Springs in Baltimore County, Maryland (Laughlin, 1966). Those studies contained 8000 well records, of which more than 1300 were statistically analyzed indicating that well yields and specific capacities showed that wells situated in valleys or draws yielded three to four times as much water as wells on hilltops or divides. Except for wells in marble, little significant difference was observed for the yield of wells in different rock types. The best well yields were expected where wells in a valley intersected two or more extensive weathered joint or fracture systems. The deep bedrock portion of a crystalline rock aquifer is unweathered crystalline rock and contains little void space; consequently, most of the groundwater must be stored within the shallow water table, in the weathered zone or saprolite, to sustain wells during extended drought periods.

Nutter (1974) described the well yields of bedrock aquifers in Maryland. In 1945 Maryland required drillers to obtain permits to drill and to file completion reports for water wells. At least 80 percent of the well records published in Maryland groundwater reports are domestic and farm wells. In many cases these wells are located on ridgetops or upland areas where low yielding wells are expected to occur. Well sites are also usually selected relative to the location of the house and septic system. Since domestic water use only requires about 3 gpm, drillers tend to stop drilling when enough water is obtained. Domestic wells exceeding 200 ft are completed in bedrock and almost all have low yields. After completion, nearly all domestic wells are tested by pumping with compressed air. Until about 1974, pumping tests were normally run for 1 or 2 hours on domestic wells, but new regulations then required longer pumping tests for most wells. Both fracture-trace and topographic methods for selecting well sites seem to be more successful in limestone valleys, the Piedmont, and the Blue Ridge rather than in the sandstone and shale aquifers of western Maryland and the Frederick Valley, in which water flow is primarily controlled by near horizontal bedding plane features. Due to the limited storage capacity of most bedrock aquifers, the yield of wells frequently declines during extended periods of pumping, especially during droughts, when well yields determined from short duration pumping tests may be twice the actual supply available under stress.

In the Nutter (1975) study, it is indicated that the Triassic-rock aquifers of Maryland were a reliable source of water for domestic, farm, and small commercial use; with 93% the wells inventoried having yields more than 3 gpm. Factors affecting well yields were geologic structure (presence of joints and faults), topographic position, lithology, and well depth. Topography is important because stream networks tend to be aligned along major joints and faults; therefore, wells drilled in valleys or draws are more likely to intersect water-bearing fractures than wells drilled on hilltops. Lithology is also an important factor influencing the yield of wells. The limestone-pebble conglomerate contains many of the highest yielding wells in the study area. Sandstone and conglomerate beds are likely to yield more water to wells than are shale and siltstone beds, because joints tend to be more closely spaced in sandstone and conglomerate formations. Water-bearing zones in the Triassic-rock aquifers can occur at depths greater than 500 ft, so it is important to drill wells deeper than the general maximum of 300 ft in crystalline rock aquifers.

Otton (1981) reported that the Maryland Water Resources Administration defines that the minimum domestic well yield shall be not less than 250 gallons of water for a 2·hour period (2.1 gpm) and capable of producing this quantity at least three times (750 gallons total) during any one 24-hour period or 0.5 gpm. Western Montgomery County is underlain by pre-Triassic crystalline phyllite and schist, Triassic shale, siltstone, and sandstone, terrace deposits of Tertiary age, and surficial alluvial deposits of (?) Quaternary age. The median specific capacity of 21 crystalline-rock wells was 0.18 gallon per minute per foot (gpm/ft) Similarly, the median specific capacity of 80 wells in the consolidated sediments was 0.15, which suggests little significant difference between the two major rock types. During a dry period in 1978, the Otton (1981) investigation reported that the yield of the four public-supply wells at Poolesville declined by about 36 percent, based on two comparative 60-day periods.

Burgy and Duigon (2012) conducted a pilot study in Frederick County and the nearby areas surrounding Poolesville (Montgomery County), Taneytown, Mt. Airy, and Westminster (Carroll County), Maryland, to evaluate factors related to well yields. Data from 2,315 wells were analyzed to determine if there are any relations between well yield and geology, well depth, well construction, or other factors in fractured-rock aquifers. Depth to bedrock (overburden thickness), position of the water table relative to the bedrock/overburden interface, and distance to a mapped fault did not demonstrate any significant influence on well yield. Well yields are significantly higher in public-supply wells and commercial/industrial/institutional wells than in domestic wells. Public-supply and the other non-domestic wells are generally sited by a professional geologist/engineer, have more freedom in locating the well and greater funds available for construction and development, and are designed for maximizing the potential yield. Domestic wells, by comparison, are typically drilled to meet a minimum yield and depth requirements. Geologic units were assigned to one of four lithologic categories: carbonate, fine-grained siliciclastic, coarse-grained siliciclastic, or igneous rocks. Wells completed in the Triassic rocks, on average, had greater well yields than wells located in the Piedmont and Blue Ridge. The wells located in carbonate rocks had the largest average yields for equivalent depths.

The present water well construction regulations (Code of Maryland Regulations) require that a domestic well or double well combination shall produce a minimum yield of 1 gpm for 6 hours, except for mandatory pumping yield tests of wells completed in Hydrogeologic Area 3 (Piedmont and Blue Ridge), unless waived in the County Water and Sewer Plan, and where delineated in County Water and Sewer Plans for Areas 1 (unconfined coastal plain), 2 (confined coastal plain), 4 (Valley & Ridge, Appalachian Plateau) and 5 (carbonate aquifers). After a pump and related equipment are installed, pumping shall begin at a rate of withdrawal greater than 8 gpm until the water level drops to a point close to the pump at which point the pumping rate shall be adjusted so that the water level remains constant. The minimum approved yield is 1 gpm for 6 hours of continuous pumping after the well has been pumped out. The pump test may be terminated early if the well cannot be pumped out after 3 hours pumping or yields 4 gpm or greater for 3 hours continuous pumping, after the well has been pumped out. The water supply system shall produce not less than 500 gallons of water in a 2-hour period (4.2 gpm), at least once each day. If that is not the case, then sufficient storage shall be provided. If well storage is selected, the amount of storage required is calculated by subtracting the well's yield over a 2-hour period from 500 gallons.

Prior to the early 1990s, a similar method was commonly used by professional geologists/engineers in Maryland for single-well 24-72 hr hydraulic tests of public water supply wells such that stabilization of the water level in a pumping well was achieved, either by producing an apparent equilibrium at a constant rate or by reducing the pumping rate as the test proceeded. A review completed by MDE of production and monitoring records collected during the 2002 drought from 97 wells and two springs of municipal purveyors and a few golf courses in the fractured rock areas of central Maryland indicated that the average maximum drought production was only 54% of the estimated yields using those methods, Hammond (2004).

Table 16. Replacement water wells in Maryland for the period 1996-2003, with emphasis on 2002 and Carroll and Queen Anne's Counties.

Year	Allegany	Anne Arundel	Baltimore	Baltimore City	Calvert	Caroline	Carroll	Cecil	Charles	Dorchester	Frederick	Garrett
2003	77	801	661	73	641	231	46-457/584	702	569	259	500	341
2002	71/86	1054/1214	767/907	104/147	627/701	243/266	236-819/920	654/764	532/647	218/241	474/541	284/330
2001	96	1316	694	143	657	280	93-448/545	706	562	211	420	343
2000	89	1129	621	140	643	266	46-434/573	566	587	178	470	300
1999	117	1283	647/784	144	674	310	85-511/573	579/659	681	233	506/ 531	303
1998	112	1209	616	89	656	281	87-473/581	618	573	215	490	298
1997	107	1071	688	173	696	275	92-466/571	574	612	224	457	302
1996	110	1024	745	302	629	201	44-385/480	531	454	191	321	270
Avg w/o 2002	101	1119	671	152	657	263	70-453/558	622	577	216	443	308
Replace 2002	10	483	386	3	143	88	236	205	196	78	127	55
% Total 2002		46	50	3	23	36	29	31	37	36	27	19
Replace 1999			154				85	164			84	
Total All Years	7,629	75,987	47,944	7,090	25,666	11,519	40,547	28,320	20,921	11,136	37,331	15,131
% All Years	0.13	0.64	0.81	0.04	0.56	0.76	0.58	0.72	0.94	0.70	0.34	0.36

Year	Harford	Howard	Kent	Montgomery	Prince George's	Queen Anne's	Somerset	St. Mary's	Talbot	Washington	Wicomico	Worcester
2003	606	330	161	380	330	87-262/326	124	792	257	365	677	306
2002	670/820	314/359	141/172	359/430	231/280	296-514/549	122/137	644/739	267/300	447/508	735/792	351/397
2001	547	414	183	313	352	90-348/392	119	628	301	322	674	325
2000	559	409	168	334	287	89-309/348	145	656	263	320	643	312
1999	576/654	410/523	161	333/384	308	136-396/446	170	715	346	314/341	694/843	421
1998	711	546	198	300	344	119-357/394	143	759	331	352	785	342
1997	644	407	175	338	287	93-332/374	143	713	259	296	699	321
1996	511	423	136	221	475	90-283/321	121	637	257	362	734	316
Avg w/o 2002	525	436	169	324	340	101-327/325	138	700	288	337	722	335
Replace 2002	250	71	54	38	53	296	65	258	119	98	228	156
% Total 2002	37	23	36	11	23	58	53	40	45	22	31	44
Replace 1999	118	66		30		136				45	164	
Total All Years	36,096	23,077	8,663	23,088	15,649	20,199	9,064	29,200	14,034	18,852	32,829	14,697
% All Years	0.69	0.31	0.62	0.16	0.34	1.47	0.72	0.88	0.85	0.52	0.69	1.06

With nearly 200,000 domestic wells in the fractured rock areas of Maryland, it is unlikely that any analytical method could be developed to directly determine the effects of climate change on those wells. The errors involved in estimating domestic well yields (>50%) are much greater than those generally thought for the effects of climate change on recharge (± 10%) in Maryland. During the drought of 2001-2002, there were reports of numerous domestic wells being replaced in fractured rock counties due to declining yields. The average effective recharge (baseflow) during the drought year 2002 was about ½ of the long-term effective recharge in the fractured rock counties and the impacts caused by that drought might be used as proxy for the effects of climate change. A review of the well reports on the MDE SDWISPLUSDATA Report Server was conducted to estimate how many, of the mostly domestic, wells were replaced due to the drought. Table 16 provides the results of that review for the period 1996 to 2003, which included the droughts of 1999 and 2002 and the very wet years of 1996 and 2003. One problem was that each year's data included records from other years, mostly the preceding year. The corrections after deletions of other year's data are shown in red for the 2002 drought for all counties, the 1999 drought for the fracture rock counties plus Wicomico County, and all years for Carroll and Queen Anne's Counties. After the corrections, the number of replacement wells were tabulated and shown in the purple for all counties in 2002, selected counties in 1999, and all years for Carroll and Queen Annes Counties.

It appeared that the maximum number of wells replaced in 2002 relative the average of the other years was greatest for Baltimore, Carroll, Harford, and Queen Annes Counties, which were potentially the counties most impacted by the drought. A second analysis was conducted for those counties and for control purposes, Anne Arundel and Wicomico Counties, Table 17. This consisted first of tabulating all the wells replaced during the period 1996 to 2003, from which wells from other years were deleted. The corrected percentage of actual vs total wells completed for the six counties varied from 84% to 92%, with an average of 88%. The total number of wells completed for all years was then corrected using a factor of 88%, producing a total for the State of 506,000 wells. The number of wells replaced during the drought of 2002 was estimated by subtracting the average number replaced during the period 1996 to 2001 and 2003 from the number replaced during 2002. The percentage of wells replaced in 2002 was 0.15% and 0.19% in Anne Arundel and Wicomico Counties, respectively. Since those counties are underlain by confined coastal plain aquifers, these results reflect indirect drought effects due to interference from large withdrawals or are within the margin of error for predicting such impacts. The relatively larger number (0.47% to 0.60%) of wells replaced in three fractured rock counties (BA, CL, and HA) was most likely due to the drought because the wells were completed in unconfined or leaky crystalline rock aquifers. The fractured rock counties west of those three counties are less affected due to differing geologic units (carbonate, fine-grained siliciclastic, and coarse-grained siliciclastic rocks) and appeared to be less affected by the drought. Cecil County was not included in the analysis because it is underlain by roughly equal areas of crystalline rock and coastal plain sediments. Queen Anne's County is somewhat unique in that a relatively high number (1.1% of total) of wells were replaced. It is likely that this was only indirectly related to the drought and was due to interference from farm irrigation wells in the confined Aquia aquifer, because of increased summertime withdrawals caused by higher temperatures. This observation should be confirmed by a detailed study identifying the locations, depths, and aquifers of the replaced wells relative to the farm irrigation wells.

Although more than 600 wells in central Maryland likely were directly replaced due to the severe to extreme 2002 drought (one of the three worst in the past 100 years), this was only about 0.5% of the total number of wells in those counties. It is then possible that the effects of climate change might not be worse than the effects of the 2002 drought, requiring a similar of number wells to be replaced.

Table 17. Total number of wells replaced in various Maryland counties vs the number replaced in 2002.

County	AA	BA	CL	HA	QA	WI	Total	State
uncorr	9047	4932	4827	5052	3150	5847	32,855	
corr	8148	4559	3993	4266	2801	5256	29,023	
% corr	90	92	83	84	89	90	88	
Total all years	75,987	47,944	40,547	36,096	20,199	32,829	253,602	574,873
Corr to 88%	66,869	42,191	35,681	31,764	17,775	28,890	223,170	505,888
2002 Drought Replaced	98	251	166	153	195	56	919	
Drought % Total	0.147	0.595	0.465	0.482	1.097	0.194	0.412	

Recommendations

In a sense Maryland is in a fortunate situation concerning the impacts of climate change on the State's water supply. In 2015, 87% of the State's public water users were supplied by surface water, primarily from the Potomac River and WMA reservoirs, and the City of Baltimore reservoirs, supplemented by withdrawals from the Susquehanna River. Both of those major water suppliers had excess reservoir capacity remaining at the end of the record (Baltimore) or near record (WMA) 2001-2002 drought. About 85% of the public groundwater use was taken from confined Coastal Plain aquifers that were unaffected by the drought, which is unlikely to change because of climate change, except for increased water demand, primarily caused by greater outdoor water due to increased evapotranspiration. Brackish water intrusion, due to pumping, has occurred in several near shore areas; however, increasing sea level rise due to climate change is unlikely to cause significantly increased intrusion at those sites. Some of the lower lying areas of Dorchester and adjacent counties may be affected by sea level rise, increasing the risk of brackish water intrusion in a few public water supplies withdrawing water from the unconfined portion of the Columbia aquifer. The remaining groundwater use was taken from the unconfined or semi-confined fractured rock aquifers of the State in central and western Maryland. The water supplies in central Maryland were most affected by the drought due to declining well yields and are likely to be the most impacted by climate change.

More information is required to evaluate the likelihood of the low flow climate scenarios in the ICPRB studies, due to the uncertainty reflected in the ICPRB studies and the substantial prediction errors of the climate response function used to predict annual streamflow and baseflow (effective recharge), based on annual temperature and precipitation data. ICPRB's next water supply study, planned for 2025, will reassess the potential impact of climate change on regional streamflow based on additional data on climate, and flow trends and projections There are certain actions that the State could use to evaluate the effects of climate change on public water supplies and what remedial actions may be required.

1. ICPRB has published a series of reports every five years since 1990. The most recent ones considered the potential impact of climate change on the WMA system resources using the complex PRRISM flow mass technique to determine the yield of the multi-reservoir water supply system. These 5-year studies should continue with the expectation that the uncertainty in the climate change models will decrease over time. The proposed upgrades to the WMA water supply system should be completed.
2. Similar 5-year studies should be conducted on the City of Baltimore reservoir system and Susquehanna River connection. The City of Baltimore, if not already done so, should complete the planned upgrade the capacity of the Deer Creek pumping station from 137 Mgd to 190 Mgd.
3. Water systems should conduct flow mass studies routinely if small water supply reservoirs or simple intakes are utilized as a water source. The study should include the potential effects of climate change on sustained yields of these types of water sources.
4. Sampling of chloride concentrations should continue at the sites where brackish water intrusion has been identified; Annapolis Neck/Mayo Peninsula, Kent Island, Ocean City and Baltimore Harbor. Additional sampling of chloride concentrations should be conducted at Bryans Road/Indian Head (Charles County) and in low lying southwestern portions of the Eastern Shore, especially along the Nanticoke River in Dorchester County

5. *The impact on the yields of wells in the Piedmont and Blue Ridge areas of Central Maryland during a drought is a major concern.* The yields of wells in service should be monitored by the collection and analysis of the following daily operational well data: Pumpage (water use), hours pumped and, as a minimum, the water level at the end of the pumping drawdown cycle. Directions for the collection of these data are given in the MDE Capacity Management Plan Guidance document: https://mde.maryland.gov/programs/water/water_supply/Documents/WaterSupplyCapacityPlansGuidance2013.pdf Accessed 1/29/2024.
   Public water systems in the area between the Fall Line and Washington/Frederick County border and Western Maryland should maintain and report to MDE this operational data. An electronic database would need to be set up to record the data in manner to allow collation, analysis and dissemination of the results demonstrating the seasonal variation and potential effects of climate change on the well yields.
6. The ICPRB Monocacy/Catoctin drainage area study, Schultz et al. (2005), should be updated to include the effects of climate change and seasonal water demand.
7. To address climate change and prepare for its impacts, the Water Supply Program should review the existing Water Appropriation and Use Permit conditions and policies to ensure permit holders can adequately respond to the effects of climate change.

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