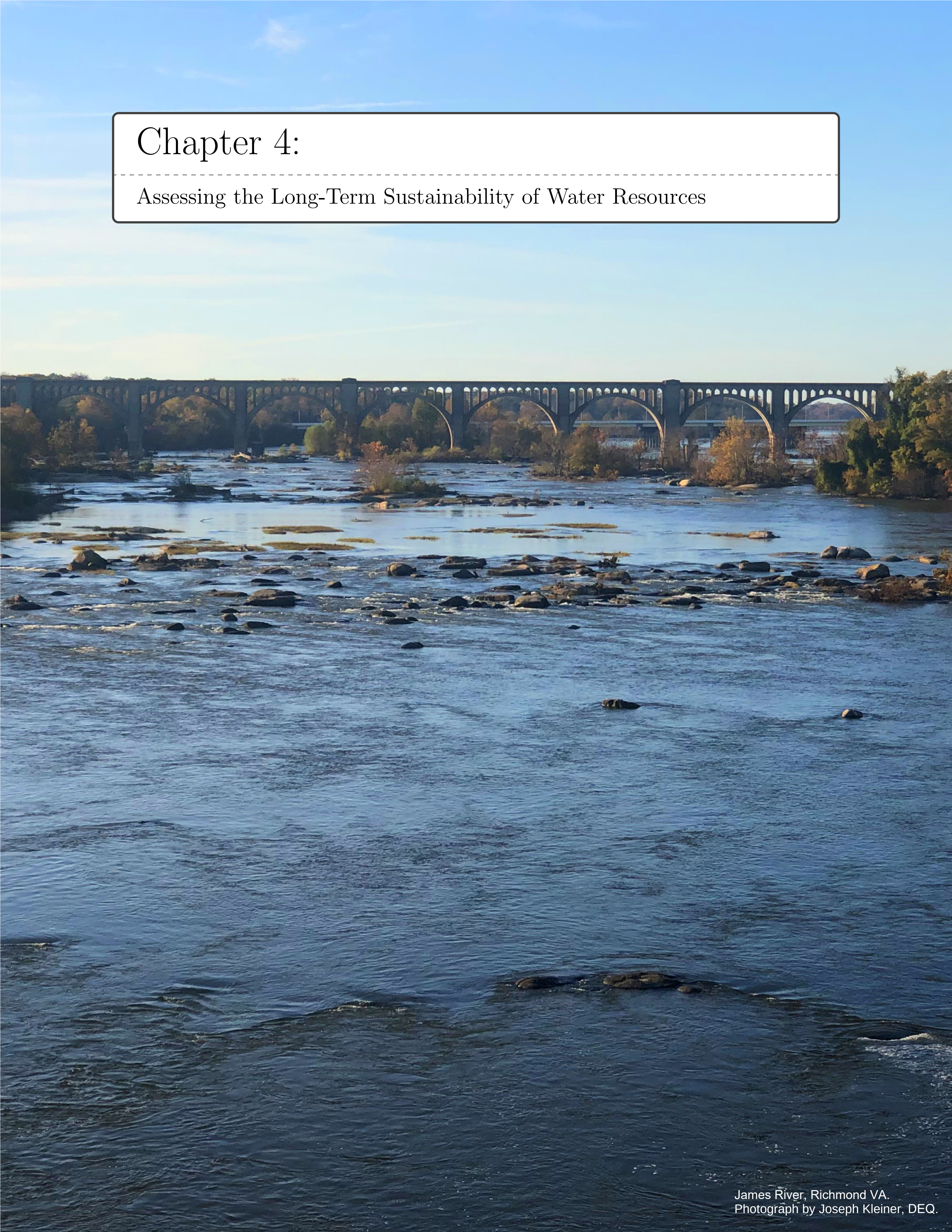
Chapter 4:

Assessing the Long-Term Sustainability of Water Resources



James River, Richmond VA.
Photograph by Joseph Kleiner, DEQ.

4 Assessing the Long-Term Sustainability of Water Resources

4.1 Introduction

The following chapter explores the methodology used to model and assess the long-term sustainability of water resources in Virginia. Included is a description of the hydrologic model itself, inputs to the model, the Cumulative Impact Analysis (CIA) approach, as well as model outputs and the metrics used to evaluate potential impacts to the beneficial uses of Virginia streams. Statewide model results can be found towards the end of the chapter in section 4.9.

The comprehensive VAHydro hydrologic model is used to evaluate surface water supply availability throughout Virginia. The VAHydro model simulates streamflow with inputs such as precipitation, climate, land use, and topography, as well as data collected through DEQ water supply planning and reporting programs including all known withdrawals and discharges, as well as operational rules of VWP permits and major hydrologic features such as reservoirs. These model inputs will be described in greater detail throughout this chapter.

The 2020 update to the VAHydro model features an expanded time span, improved handling of consumptive use (point source discharges), climate change scenarios, and higher resolution water withdrawal locations. The expanded spatial resolution of withdrawal locations facilitates analysis of impacts in HUC 10 watersheds, an approximately 10 fold increase in resolution over the 2015 plan which featured HUC 8 analysis units. The 2020 model is built on rainfall-evaporation-runoff (RER) time-series from the Chesapeake Bay Model Phase 6 which runs from 1984-2014 in the Chesapeake Bay watershed drainage, and 1984-2005 in the rivers flowing outside of the Chesapeake Bay watershed, aka the "southern rivers." Extensive efforts were undertaken by DEQ staff to link all water supply planning systems submitted by localities to corresponding facilities in the VAHydro water withdrawal reporting database. This linkage enabled the shift to HUC 10 analysis units, and allows for modeling of monthly varying use patterns based on historical reported data. These planning/reporting system linkages can now be maintained going forward, ensuring that localities will always have the most up to date reporting data to use in their assessment of current demands, and projection of future trends in water use.

To facilitate modeling and analysis in the State Plan, Virginia is divided along hydrologic boundaries into 20 sub-basin units, referred to as "Minor Basins" (Figure 14). These minor basins vary in size from around 900 mi^2 to 6,000 mi^2 and roughly contain 1-3 HUC 8 units. This chapter will highlight model results with a focus on statewide trends, with results for each individual minor basin described in greater detail in Appendix A.

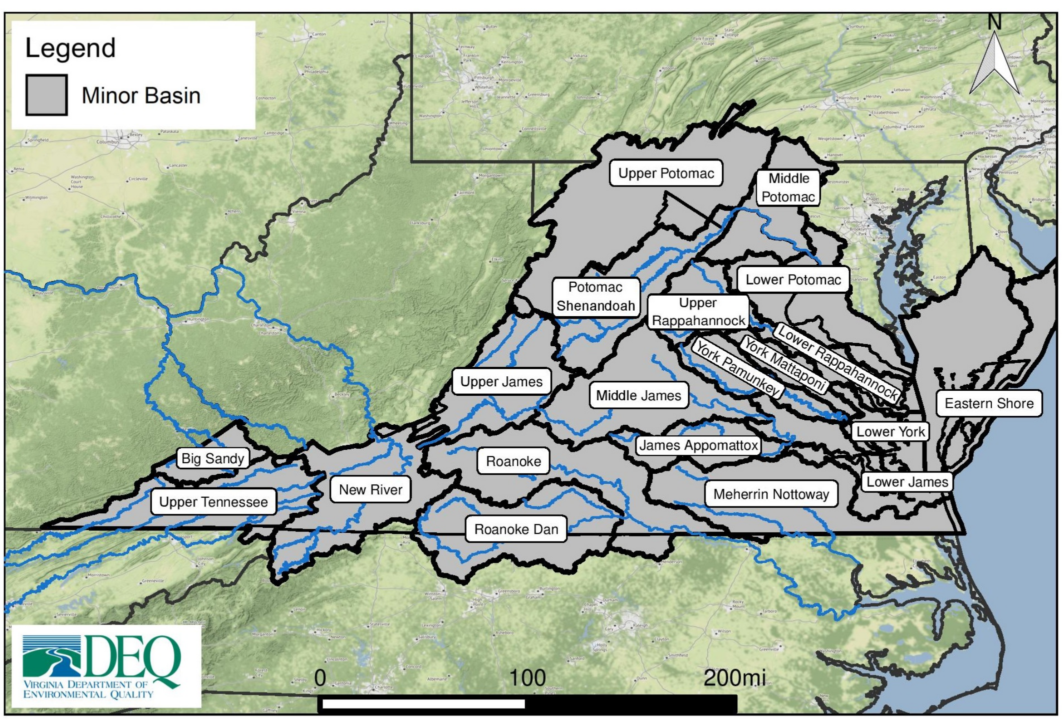


Figure 14: Minor Basin Overview

4.2 Cumulative Impact Analysis (CIA)

DEQ assesses water supply sustainability through CIA modeling. Each minor basin is divided into high-resolution hydrologic subsections called "river segments" (over 600 river segments in total), roughly the size of HUC 10 hydrologic units. The model simulates a daily water balance for every individual river segment, with each downstream segment being affected by the "cumulative impact" of streamflow changes occurring in upstream segments.

> **Cumulative Impact Analysis (CIA)** is a modeling and analysis approach that takes into account the varied hydrologic process occurring throughout a river network (including meteorology and human water use). By simulating a daily water balance for every individual river segment within a watershed, DEQ is able to evaluate the potential "cumulative impact" of all streamflow changes occurring upstream of any location within the river network.

Beneficial uses can be impacted by flow variations on an annual, seasonal, and even daily time scale. Therefore, the model evaluates cumulative impacts to the water balance on a daily basis, as well as the variation in conditions expected to occur on a seasonal and annual basis. This CIA modeling approach forms the basis for evaluating future sustainability of water supply and protection of beneficial uses at a fine scale; it is an approach that has been used in DEQ's permitting and planning programs for decades, with constant refinement and improvement over time.

4.2.1 VAHydro Surface Water Model

DEQ develops and maintains the VAHydro web-based platform for water resource management in Virginia. A primary component of the VAHydro system is the VAHydro surface water model, which is used to perform all CIA modeling. The VAHydro surface water model is comprised of the Phase 6 Chesapeake Bay Program (CBP) watershed model[39] at its foundation, with several key DEQ enhancements including high resolution intake locations and withdrawal amounts, point sources, permit and reservoir operations, land use, and in some cases in order to provide detailed facility operations, additional river segmentation beyond those river segments included in the Phase 6 model.

As noted, the model features an RER hydrology time-series which spans 1984-2014 in the Chesapeake Bay watershed drainage, and 1984-2005 in the southern rivers portion of the state. The multidecadal model time periods, for both the northern and southern rivers portions of the model, are considered representative, and thus expected to show the full range of seasonal and annual climatic variations including "average" years, "wet" years, and "drought" years. The RER provides a baseline flow time series, or an estimate of the water entering the riverine system on a daily basis. Applied to this baseline are the demands on the riverine system such as water withdrawals, discharges, operational rules for water supply entities, and projected climatic variation. These inputs to the model are discussed in greater detail below.

4.3 Model Inputs

4.3.1 Meteorology

Similar to river segments, the VAHydro model contains a layer of land units based on political boundaries referred to as "land segments" (around 150 total). These regions are delineated according to county and city designations, with some areas being further divided along physiographic boundaries. Land segments are the units used in the VAHydro model for simulating meteorological inputs including rainfall, temperature, snowfall, potential evapotranspiration (PET), dewpoint, wind, solar radiation and cloud cover. This water supply plan analysis contains simulations based on historical meteorological conditions as well as a range of climate change projections (see 4.5.2).

The foundation of the VAHydro hydrologic model is HSPF[40]. HSPF is capable of simulating a continuous runoff flow rate, as well as nutrient and pesticide concentrations and sediment loads throughout a watershed. To provide continuous input data for HSPF, the model uses hourly input data derived from statistical analysis of observed precipitation data from measurement stations for the model time period (1984-2014, or 1984-2005). As noted,

[39] CBP Modeling; Phase 6 CBP watershed model
[40] HSPF - DOI: 10.1061/(ASCE)EE.1943-7870.0000555

the model can be described as RER with the primary components of rainfall and evaporation driving the volume of water runoff from a particular land segment, with hydrologic processes such as infiltration used to calibrate the simulation to achieve an overall water balance. Although the model provides data at an hourly timestep, most water supply planning model runs are performed using a daily timestep (This generally minimizes model errors and results in improved accuracy).

4.3.2 Land Use

A third layer of "land-river segments" consists of an intersection between the river segment and land segment layers. Land-river segments function to route flows, nutrient loads, and sediment sources from land segment model simulations to the river segment models. This is achieved through high-resolution land-use model inputs. The VAHydro model includes tabular land use estimates for every land-river segment in the model.

Northern Rivers: This land use data was generated during the development of the CBP Phase 6 watershed model, using USDA Census of Agriculture and other state and county data sources. The process of generating the land use dataset involved taking high-resolution land cover data (1m x 1m pixels) obtained from aerial imagery, and translating that data into "land use" as it's used in the CBP watershed model. Land use in the CBP's classification schema takes into account both land surface characteristics (level of impervious surfaces, vegetation, tree cover etc.) as well as how humans use the land (whether the land is used for agriculture, mining, residential etc.).

Southern Rivers: The land use dataset was updated for the southern rivers portion of Virginia through a collaborative project between DEQ and the Virginia Tech Department of Biological Systems Engineering. Through this multi-year project, land cover data was obtained from the Virginia Geographic Information Network (VGIN). Similar to the dataset for the northern rivers portion of the state, this data is high-resolution (1m resolution) and current through the year 2016. For those portions of the southern rivers that flow into Virginia from North Carolina and Tennessee, an additional dataset was obtained from the National Land Cover Database (NLCD) at a 30m resolution, current through 2011. Similar to the process used in the CBP watershed model, this project translated these datasets from land cover to land use in order to be plugged directly into the VAHydro hydrologic model.

Land use is an important factor when developing water quality models, however it is also of particular interest in water quantity modeling in the context of this State Plan. Land use inputs are significant for their effects on processes such as infiltration, runoff amount, and effects on streamflow. The VAHydro model uses the unit runoff values associated with each land use type to generate surface runoff totals for each land-river segment. This land-river segment runoff value represents the amount of water that enters the river segment model associated with the land-river segment. Since a particular river segment may have several associated land-river segments, the total runoff entering the river segment channel is equivalent to the summed total of runoff from each of its associated land-river segments. Included in the VAHydro model are land use inputs for historic, current, and projected future conditions.

4.3.3 Withdrawals

Water Supply Planning Inputs - The primary water use inputs to the VAHydro model planning scenarios are sourced from the data provided by 48 Local and Regional Water Supply Plans as discussed in chapter 3. The data collected includes system and source level data including surface water withdrawals, groundwater withdrawals and purchased transfers of water between systems/localities. In order to evaluate different use types, these demands are categorized as either Agriculture, Community Water Systems, Large Self-Supplied Users, or Small Self-Supplied Users. The comprehensive VAHydro system allows the data DEQ collects through the water supply planning program to be fed directly into the VAHydro surface water model (See Figure 15).

Estimates of current water demands submitted through water supply plans provide the basis for the 2020 "current" modeling scenario (See section 4.4 for additional notes on scenario development). Included in each water supply plan are future projections for every water supply planning system based on projected population and demand changes. Applying this projection data to the 2020 demands provides a reliable method of estimating future demand. The "future" demand scenarios developed for this State Plan include decadal simulations for the years 2030 and 2040. The 2040 projected demands are also applied in additional modeling scenarios for evaluating the potential impacts of climate change (Section 4.5).

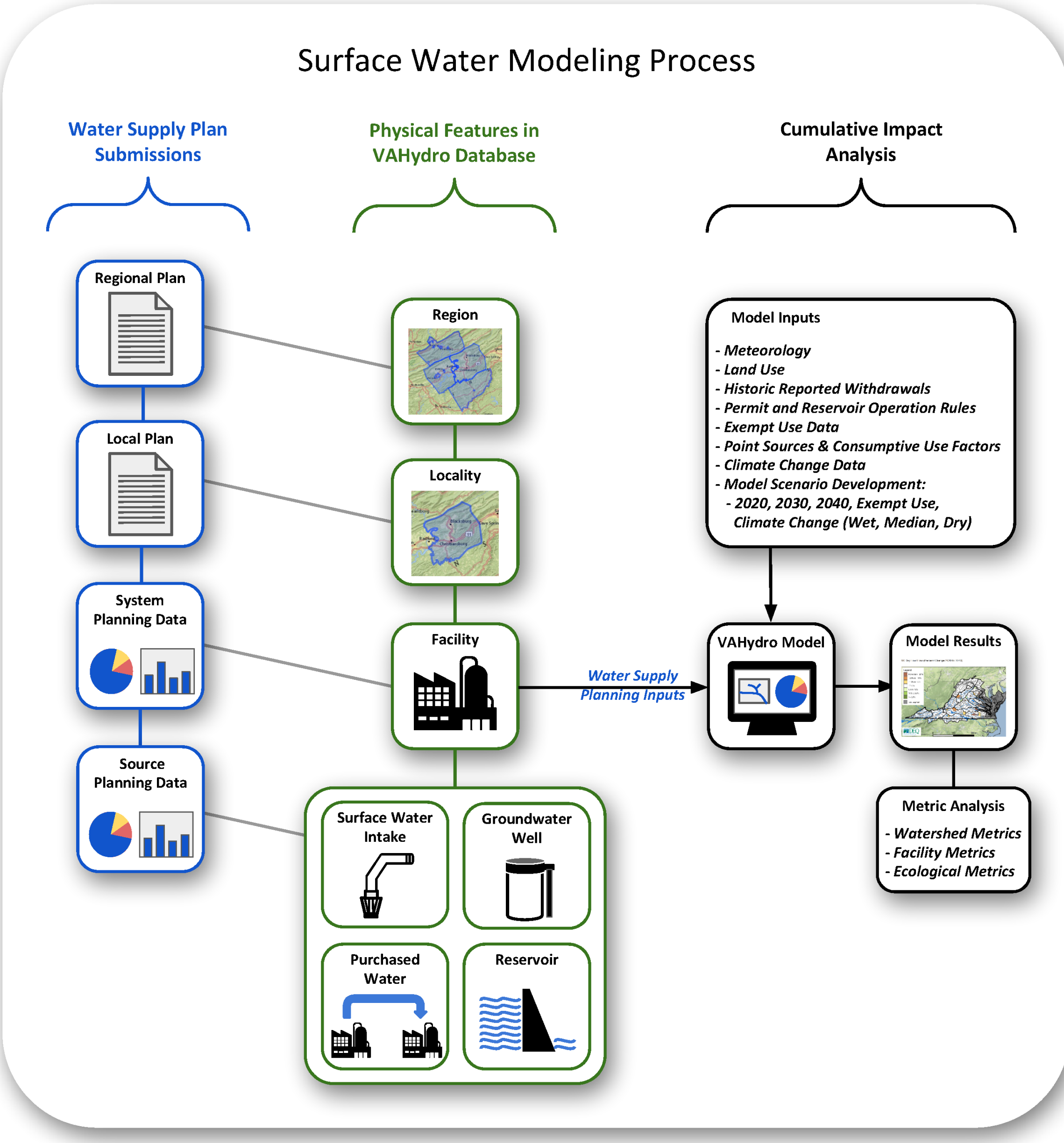


Figure 15: Surface Water Modeling Process

Historic Reported Withdrawals - The VAHydro data system serves as the electronic reporting interface and data repository for annual water withdrawal reporting. VAHydro stores monthly and annual withdrawal data dating as far back as 1982. Additionally, permit withdrawal data reports are entered into the VAHydro system on a quarterly basis. In this way VAHydro always has the most up-to-date withdrawal data possible, with new withdrawal data being entered regularly.

Beyond serving as a means of data entry and storage, the VAHydro system allows the withdrawal data to feed directly into the VAHydro hydrologic model. This data becomes critical for instances where a withdrawing facility is absent from a water supply plan, or where high-resolution location information isn't included in a water supply plan for a particular water system. In 2019 DEQ staff linked all the systems present in water supply plans to existing facility features already present in VAHydro due to annual reporting. This process ensures that each water supply plan demand is modeled with the greatest possible spatial accuracy, since facility withdrawal locations may be updated regularly by water users through the VAHydro electronic reporting interface.

Historic reported withdrawals also help to significantly improve model accuracy through the historic monthly distribution of reported water use. Monthly factors are generated using the past five year's worth of reporting data for every facility in the VAHydro system. By multiplying water demands collected through the water supply planning process (2020, 2030, 2040 demands) by these monthly factors, projected demands can be modeled seasonally.

Additional surface water model accuracy is gained through the partitioning of surface water and groundwater demands. Many water supply plan systems have both groundwater well and surface water intake sources. System level demand data submitted in water supply plans is not always separated into volumes by source type. By taking historic facility reporting data into account, the fraction of a facility's water use that historically comes from surface water can be determined. This surface water fraction is fed directly into the VAHydro model as a multiplier for water supply planning data inputs to ensure proper accounting of surface water demands.

Permit and Reservoir Operation Rules -

Permits **-** All VWP surface water permits issued by DEQ are accounted for in the VAHydro model (see Chapter 1 for VWP Permit Program Regulation and additional notes on the permitting process). VWP permits are entered into the VAHydro model during the initial permit application process. This allows DEQ to evaluate potential permits with by conducting a CIA using the applicant's water demand to assess potential impacts on existing in-stream and offstream beneficial uses.

Once permits are issued, they remain in the VAHydro model, complete with any operational rules as outlined in the permit. This includes any specific flow-by requirements as outlined in the permit, tiered or seasonally varying withdrawal operations, demand partitioning between surface water and groundwater sources for facilities with both wells and intakes, or any additional low flow or water quality requirements. These VWP operations are modeled explicitly in regular CIA model runs, as well as the water supply planning model scenarios evaluated in this State Plan. The incorporation of VWP permit operations into the model helps ensure a proper accounting of the local water balance, which in turn allows for an accurate assessment of potential impacts to downstream water availability for other existing intakes, aquatic life, water quality or recreational uses.

Reservoirs **-** Many reservoirs are explicitly modeled in the VAHydro system. This means the model has been resegmented and parameterized to include a high-resolution reservoir model. These models include detailed information including stage-storage-surface area tables, maximum capacity, amount of unusable storage, riser structure dimensions, tiered flowby/release rules, and other reservoir-specific water supply management operational information. The inclusion of these reservoir features in the model provides a more accurate simulation of reservoir storage and impacts on the flow regime such as timing and magnitude of streamflow, flow attenuation, evaporation, and effects on flow under drought conditions.

Incorporating reservoir models into the VAHydro system also allows for an improved simulation of potential impacts to users withdrawing from within a reservoir. This is critical for evaluating changes in reservoir storage that may impact user's withdrawals. This is of particular importance for simulating times of extreme drought, when reservoir storage may become insufficient to meet surface water demand. In some cases where a VWP permitted facility is not directly withdrawing from a reservoir, that withdrawal's operations may still be closely linked to a nearby reservoir. This is due to withdrawal rules that often depend on storage remaining in a particular reservoir. The VAHydro model is equipped to handle these unique situations and can provide an accurate evaluation of water availability.

4.3.4 Point Sources & Consumptive Use

In order to provide an accurate accounting of the overall water balance, point source discharge estimates are accounted for in the VAHydro model. Many facilities that withdraw water throughout Virginia ultimately return some portion of their withdrawal volumes back to the stream network through point source discharges. The term Consumptive Use (CU) refers to the fraction of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise not returned to the immediate water environment. By ensuring CU is considered for every facility, the VAHydro model is capable of simulating and maintaining a more realistic water balance. This topic is covered in depth in section 4.7.

4.4 Model Scenarios

This iteration of the State Plan features a set of 7 unique model scenarios, designed to simulate a range of potential meteorologic and withdrawal demand conditions, and the resulting cumulative impact effects. See Table 9 for scenario abbreviations, meteorology and demand information. Scenarios were developed to assess potential impacts to streamflow and water availability resulting from projected future water demand by the years 2030 and 2040 as compared to "current" 2020 demands. Climate change scenarios were developed to help examine how streamflow is impacted when 2040 demands are simulated in conjunction with a range of potential precipitation and temperature conditions that may occur under a changing climate. An additional scenario was developed to evaluate potential impacts resulting from users excluded, or exempt, from VWP permit requirements by 9VAC25-210-310. This scenario is discussed in more detail in Section 4.6. These scenarios form the foundation for all cumulative impact analyses presented throughout this State Plan. Results are presented in the following statewide results Section (4.9) and minor basin focuses found in Appendix A.

Table 9: Model Scenario Overview

Scenario Abbreviation	Meteorology	Water Demands	Area Modeled
2020 "Current"	Current Conditions	2020 Demand	Statewide
2030	Current Conditions	2030 Demand	Statewide
2040	Current Conditions	2040 Demand	Statewide
Dry Climate	Future "Dry" Climate Change Conditions	2040 Demand	Northern Rivers
Median Climate	Future "Median" Climate Change Conditions	2040 Demand	Northern Rivers
Wet Climate	Future "Wet" Climate Change Conditions	2040 Demand	Northern Rivers
Exempt User	Current Conditions	Exempt User Demand	Statewide

Scenario Descriptions:

- **2020 "Current" Scenario:** The baseline scenario was developed to model cumulative impacts under current conditions. The primary inputs are estimates of current water demands submitted through local and regional water supply plans, combined with current meteorological conditions.
- **2030 Scenario:** This scenario was developed to model cumulative impacts under future conditions for the year 2030. 2030 demands were interpolated from 2020 and 2040 demands - in other words 2030 represents the midpoint between 2020 and 2040 demands. The 2030 demand scenario utilizes current meteorological conditions.
- **2040 Scenario:** This scenario was developed to model cumulative impacts under future conditions for the year 2040. The primary inputs are estimates of future water demands using projections submitted through local and regional water supply plans, combined with current meteorological conditions.
- **Dry Climate Scenario:** This scenario was developed to model cumulative impacts under future climate change conditions. The primary inputs are estimates of 2040 future water demands using projections submitted through local and regional water supply plans, combined with future climate change meteorological conditions that are considered "Dry" based on total precipitation and evaporation changes. (See section 4.5 for specifics on climate change scenario development).
- **Median Climate Scenario:** This scenario was developed to model cumulative impacts under future climate change conditions. The primary inputs are estimates of 2040 future water demands using projections submitted through local and regional water supply plans, combined with future climate change meteorological conditions that are considered "Median" based on total precipitation and evaporation changes. (See section 4.5 for specifics on climate change scenario development).
- **Wet Climate Scenario:** This scenario was developed to model cumulative impacts under future climate change conditions. The primary inputs are estimates of 2040 future water demands using projections submitted through local and regional water supply plans, combined with future climate change meteorological conditions that are considered "Wet" based on total precipitation and evaporation changes. (See section 4.5 for specifics on climate change scenario development).
- **Exempt User Scenario:** This scenario utilizes the maximum potential withdrawal claim for exempt users, combined with permitted withdrawal limits for those users that have withdrawal permits (see section 4.6 for specifics on exempt value data sources). For users that are exempt because their demands are below the threshold that requires a permit, estimates of current 2020 water demands submitted through local and regional water supply plans are used. This scenario utilizes current meteorological conditions.

4.5 Historical Climate Trends in Virginia and Future Climate Change

Annual differences in the total water budget available for in-stream and off-stream uses is determined roughly by the difference between annual rainfall and evaporation. Meteorological data shows that temperature and potential evaporation have increased in Virginia over the course of the 20th century. Extreme droughts in most Virginia streams are the result of a combination of low rainfall during winter, which leads to depleted "base flows", combined with low summer rainfall and/or high summer evaporation [Austin, 2014]. Because climate change models predict increasing future temperatures and uncertainty in future rainfall patterns through the next 30 years and beyond, it is important to quantify the potential effect of rainfall uncertainty and higher temperature/evaporation on the water budget in Virginia streams. While there is little uncertainty about the likelihood of increased evaporation, the effect of future temperature increases on the magnitude, intensity and timing of future rainfall events is less clear.

4.5.1 Historical Trends in Temperature and Evaporation

Increasing air temperatures have been measured throughout the watersheds of the eastern United States since the 20th century, and a 2014 USGS study of temperature data from 1961-2010 showed a median monthly temperature increase of at least 1°F in 32 of 85 long term monitoring stations [Rice and Jastram, 2014]. The Phase 6 Chesapeake Bay watershed model uses observed temperature to estimate potential evaporation from 1984-2014, and suggests evaporation has increased in most of Virginia over that period, with some areas having an increase of over one inch of total annual evaporation (see example in Figure 16). In a normal year, there is 10-15 inches more rainfall than evaporation in Virginia; during extreme historical drought, the difference between total annual rainfall and total annual potential evaporation can be reduced to between 0 to 5 inches. Therefore, one additional inch of evaporative loss can result in a substantial change in available water.

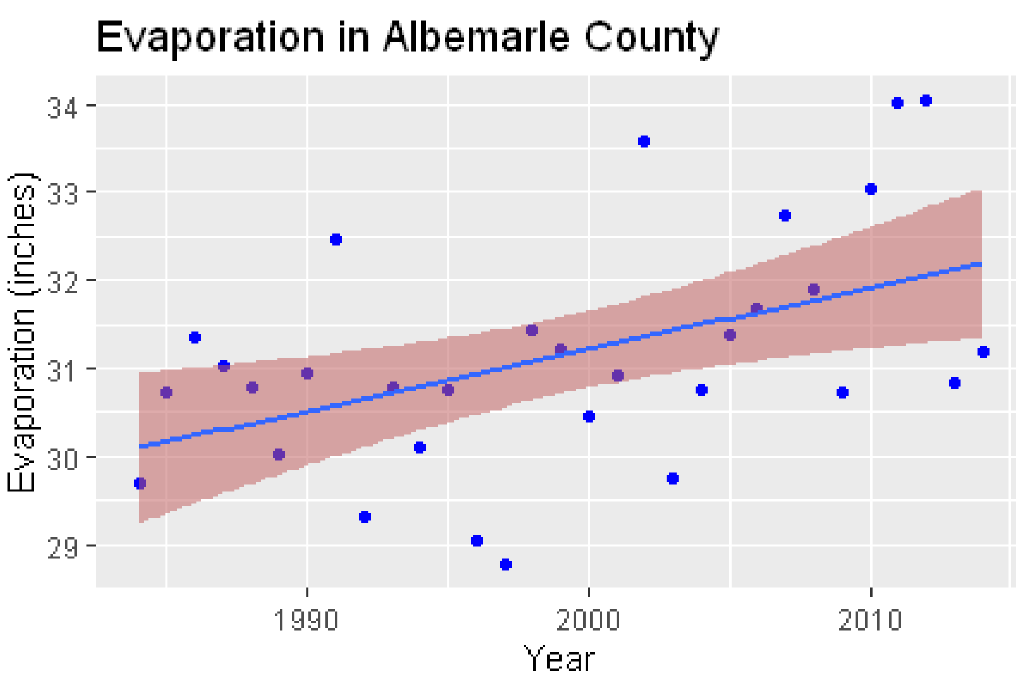


Figure 16: Estimated historical annual potential evaporation in Albemarle County, from 1984-2014 using the Chesapeake Bay Watershed Model Phase 6.

[Bhatt, 2019]

Have Increases in Historical Air Temperatures Led to Increased Rainfall? A 2017 USGS study of trends from 1960-2010 in Chesapeake bay tributaries [Rice et al., 2017] found increases in average rainfall and flow in most rivers north of the Maryland-Pennsylvania border, but no significant trends southward except for the James River which had a decrease in average flow. From the Potomac River south, the lowest average monthly rainfall also decreased, though it was not statistically significant (see Figure 17B). One limitation of this study is that it only looked at rainfall and stream flow, therefore effects from changing land cover, land use, evaporation, withdrawals or discharges were not accounted for.

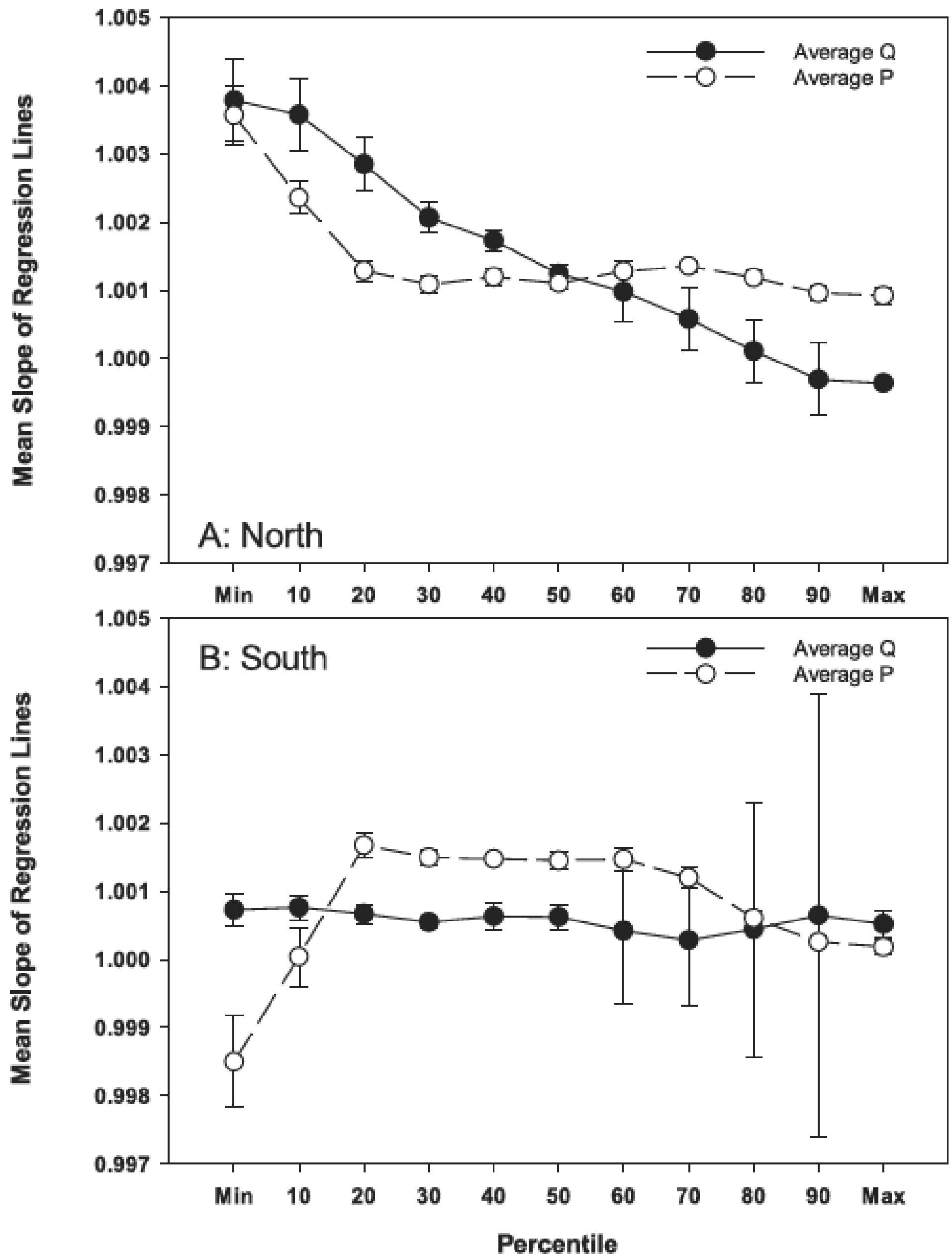


Figure 17: Changes in flow (Q) and rainfall (P) percentiles from 1927-2014 in Chesapeake Bay streams north (A) and south(B) of the Maryland/Pennsylvania border. Y-axis values greater than 1.0 show increases, less than 1.0 are decreases. Trends in the northern streams were statistically significant, while those in the south were not. Excerpted from [Rice et al., 2017].

Can Withdrawals and Discharges be Separated from Meteorological Effects in Historic Stream Flow Trend Studies?

The VAHydro model can be run with a constant withdrawal, discharge and land use in order to isolate rainfall and evaporation effects on flow. Figures 18 and 19 show a the results of a VAHydro surface water model run for 1984-2014 with a static land use, withdrawal and discharge. This model shows a trend of increasing 90 day low flows in the Potomac, and a trend towards decreasing 90 day low flows in the James. Because neither watershed has a statistically significant trend, this cannot definitely demonstrate increased or decreased drought severity as a result of climate changes over this short time period. However, agreement with the general trends seen in the USGS study, while accounting for the potential for changes in land use, withdrawals, and point sources, supports the conclusion that meteorological factors cause the apparent north-south trend in low flows in Virginia. It is important to note that [Rice et al., 2017] spanned an 87 year period, nearly 3 times as long as the CBP/VAHydro model. An expanded model time period would provide important information to understand these trends further. Future modeling efforts should also perform an analysis of annual variation in low flow in all rivers in Virginia to determine if there are other watersheds with decreasing low flow trends as a result of changing meteorology.

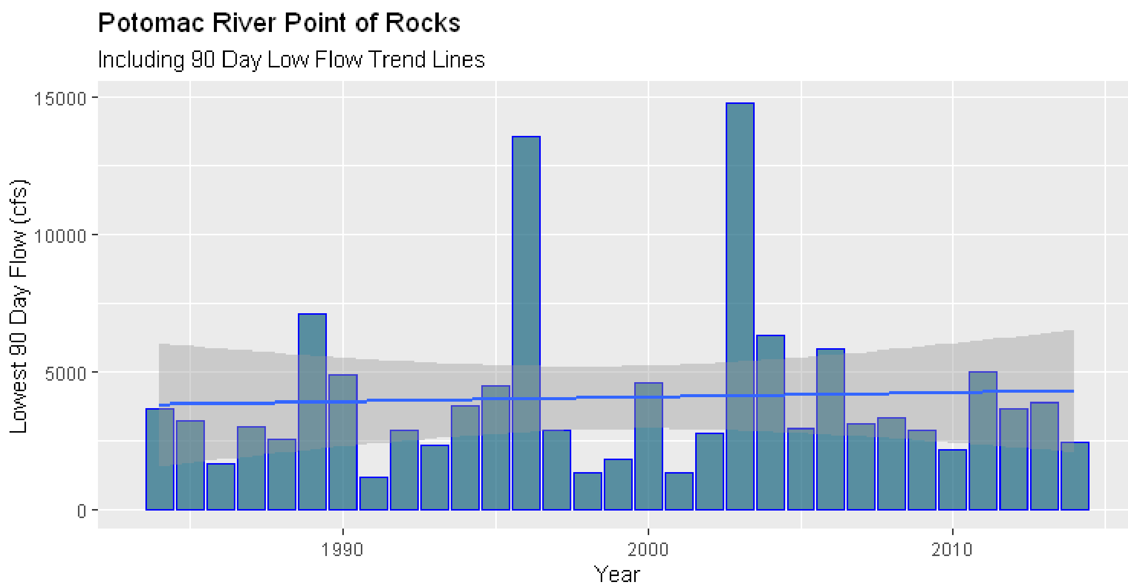


Figure 18: Annual modeled 90-day low flow from 1984-2014 using the VAHydro surface water model with historical meteorology and static withdrawal and discharge at Potomac River Point of Rocks. This model was selected because it had a constant water supply demand over time and therefore any changes to low flows are primarily due to observed changes in rainfall and evaporation. Modeled 90-day low flow had an increasing trend, but this trend was not statistically significant.

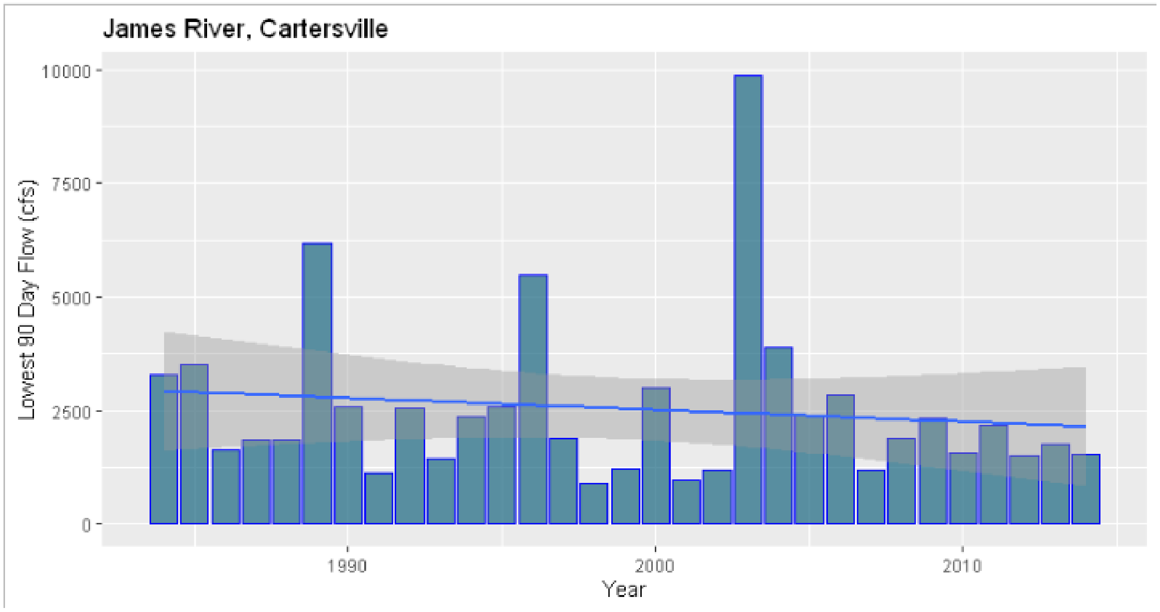


Figure 19: Annual modeled 90-day low flow from 1984-2014 using the VAHydro surface water model with historical meteorology at James River Cartersville. Changes in modeled 90-day low flows were not statistically significant.

Do Increases in Greenhouse Gas Emissions (GHG) Lead to Increases in Temperature and Evaporation?

All of the 31 global circulation models (GCMs) considered by the CBP project an increase in temperature in Virginia in all months of the year (see Figure 20) as a result of increasing greenhouse gas emissions. Increased temperature in our region results in increased evaporation from lakes and streams and increased transpiration from plants (collectively referred to as evapotranspiration). This will place additional stresses on water supply systems, especially in times of drought. An increase in long-term average temperature does not guarantee that temperatures will be higher than historic values in every single year.

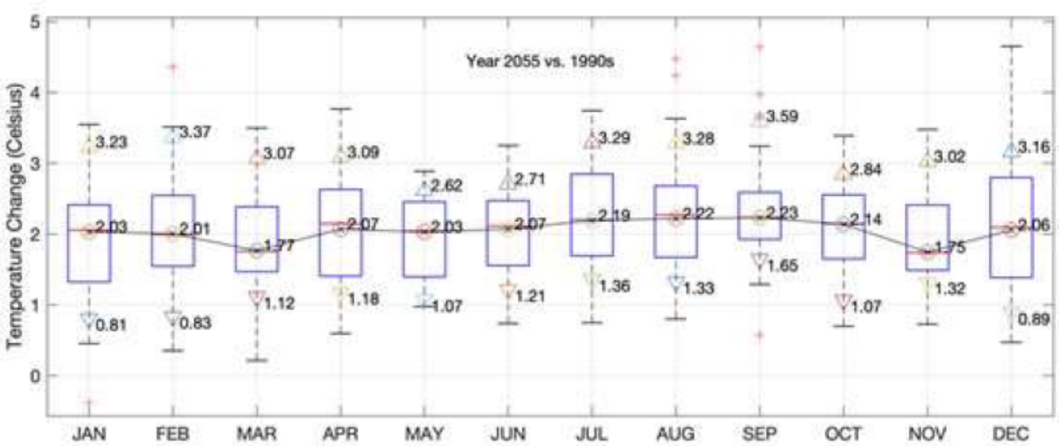


Figure 20: Box-plot showing range of monthly temperature changes, projected by the 31-member ensemble of down-scaled Global Climate Models for RCP 4.5 for the Chesapeake Bay Watershed in year 2055 [Bhatt, 2019].

Do Geographic Trends in Climate Change Models Match Observed?

Six of the 31 ensemble models considered by the Chesapeake Bay program display a similar north-south gradient to that observed in the 2017 USGS study [Rice et al., 2017].

Do Climate Change Models Predict Increasing or Decreasing Rainfall?

Of the climate models considered by the CBP, approximately 75% of scenarios project increasing mean annual and monthly rainfall, with 25% projecting no change or decreases in annual/monthly rainfall.

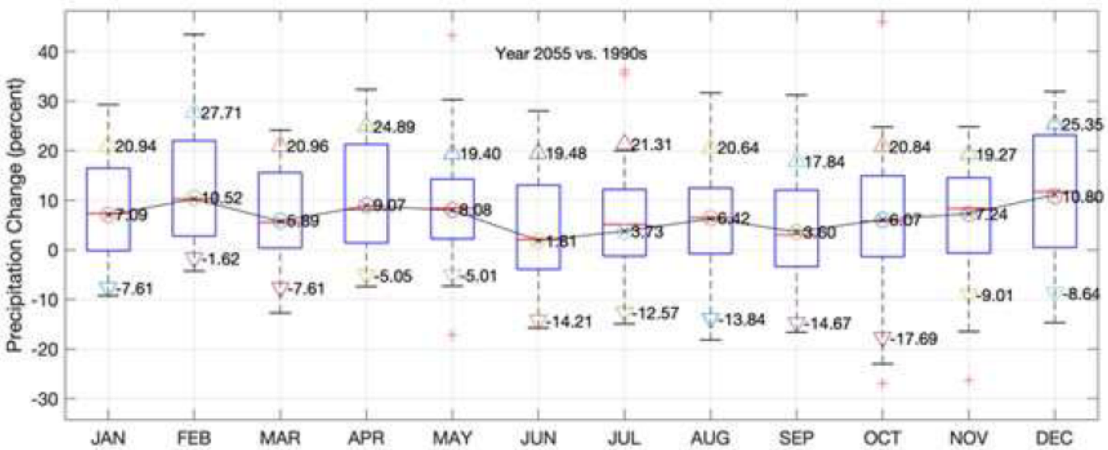


Figure 21: Range of modeled precipitation changes in the 31-member ensemble examined during development of the Chesapeake Bay model climate change analysis. Approximately one in four models suggest decreases in precipitation by 2055, while three of four suggest increases.

What is the timespan of the climate change model simulation?

The climate change model runs from calendar year 1990 through the end of calendar year 2000. This is consistent with TMDL analysis time frame, but also consistent with the convention of calculating changes to global temperature after 1990. Because this is only a 10 year window, it is likely that many watersheds have a historical low flow period that is outside of the climate change simulation time period. Of the 270 river segments modeled in Virginia, 173 have a simulated lowest 90 day flow period that falls within the 1990-2000 (climate simulation) time period. The remaining 97 river segments have a lowest simulated 90 day period that falls outside the 1990-2000 period. For these segments, it can be assumed that the climate driven flow decreases during an extreme drought could be more severe than those simulated here.

What are the Areas of Greatest Certainty and Uncertainty Regarding Climate Change?

While the amount of temperature increase by 2040 due to greenhouse gases is not known, emissions are expected to continue, and average annual temperature will therefore continue to increase to some extent. These increasing temperatures will result in greater evapotranspiration losses. The ensemble of GCM models differ with respect to changes in average annual rainfall, 25% of the models project a decrease, the remaining 75% project an increase in our region. Evaporation varies in a narrow range from year to year, whereas precipitation can differ by a factor of two between wet and dry years. However, a model analysis from 1984-2014 suggests an increase in ET of as much as one inch in Virginia during that time period, and 90% of the GCMs project at least one inch more potential evaporation by 2055. If Virginia watersheds are subject to one inch in additional annual evaporation during a severe drought, it can result in a 5-10% decrease in 90-day low flow. High precipitation years are nearly certain, but a cessation of low precipitation years is not, as evidenced by significant portions of Virginia being affected by droughts in 2001-2002, 2007-2008, 2010-2011, 2017, and 2019. Each of these instances would be exacerbated should an additional inch of evaporation become the norm during droughts.

4.5.2 Climate Change Model Meteorology in the State Plan

The climate change simulations completed for the 2020 State Plan use precipitation and evaporation inputs drawn from a set of three different climate change models selected by the USGS and Chesapeake Bay Program modeling team. These models vary from low to high in their total precipitation and evaporation changes, and are referred to in this document as the “Dry”, “Median” and “Wet” climate scenarios (more details can be found in section 4.4). Overall, evaporation changes in the Dry, Median, and Wet scenarios ranged from +1 inches to +2.5 inches, and rainfall varied from -3 inches to +12 inches per year. Of the three scenarios, the dry scenario is the only one that resulted in widespread reductions in drought flows and therefore substantial potential for water supply system impacts. The dry scenario results in an average of approximately 3 inches less rainfall, and around one more inch of evaporation, during a drought year. There was significant geographic variation in dry scenario impacts across the Commonwealth, however, variations over small geographic distances, especially in headwater watersheds, can not be used to predict the precise location of impacts. Results of the climate models should be viewed as a major basin level planning tool that can support the development of adaptive management strategies based on different combinations of future rainfall and temperature change as predicted by the best available global climate models. For more information on the 31 model ensemble evaluated by the USGS and Chesapeake Bay Program modeling teams see [Bhatt, 2019].

4.6 Exempt User Scenario

This plan includes a detailed examination of potential impacts from users excluded, or exempt, from VWP permit requirements pursuant to 9VAC25-210-310.[41] The exempt user modeling scenario was developed to evaluate the potential impacts of exempt user withdrawals. This scenario utilizes the maximum potential withdrawal claim for exempt users from the sources mentioned above, in combination with permitted withdrawal limits for those users that have VWP permits. Additional notes on the methods and assumptions of this scenario are outlined below.

A primary driver for this exempt demand analysis is to decrease uncertainty in permit analysis. Cumulative impact analysis for new permit applications considers the allowable withdrawals of all users that share a source, usually within a common river basin, in order to minimize conflicts among beneficial uses during times of drought. Permitted intakes are assumed to be at the maximum permitted withdrawal in these analyses. Intakes that are exempt from VWP permitting present a difficulty in that their presumed exempt amounts are often far larger than current demands. However, these facilities could conceivably operate at these amounts, so it is important that they be considered. A number of different data sources are commonly referenced by water users claiming an exemption. The size of the exempt claim can vary widely for a given intake depending on the data source referenced. Particularly when multiple exempt users share a source, the cumulative variation in potential withdrawals for that source can be significant. For the purpose of the State Plan, the sources of data evaluated for exempt withdrawals include:

- Estimated intake maximum capacity.
- The "safe yield" of the stream at the intake location, which was historically estimated as the lowest single day flow that occurs once every 30 years at intake location (1Q30).
- The estimated maximum daily pump capacity as reported to VDH.
- The maximum single monthly withdrawal prior to July 1989.
- A 2009 DEQ Request for Information (RFI 2009) to registered users for their presumed withdrawal exemption based on historic use before July 1989 and intake capacities.

[41] 9VAC25-210-310

Tables 10 and 11 summarize withdrawal amounts by each exemption data source type for tidal and non-tidal withdrawals. Data source types "VWP Permit" and "401 Certification" are those that are permitted by DEQ's VWP program, or by the U.S. Army Corps of Engineers respectively. The source type "Below Permit Threshold" represents users that are excluded because they do not withdraw a large enough quantity to require a permit. For these users, the 2020 water supply plan demand was used for modeling purposes. This is in contrast to all other exempt categories which do withdraw sufficient quantities of water to require a permit if they were not otherwise exempt.

The exempt user model scenario for the State Plan evaluates the worst case scenario by using the highest possible exemption claim for all exempt intakes and the current maximum permitted value for all VWP/401 permitted intakes. There are over 1,500 exempt intakes in Virginia, and using the largest exemption value for all intakes results in approximately 10 BGD from non-tidal waters - more than 7 times the current annual average daily use. A table of all demands in this scenario can be found in Appendix B - see Table ??. While consumptive withdrawals from tidal waters may still exhibit negative impacts due to significant consumptive use, a cumulative impact was not performed for withdrawals from tidal waters. Because the magnitude of exempt withdrawals in tidal waters is large, approximately another 10 BGD, this may need to be a subject of further study and should be considered in future efforts to evaluate tidal withdrawals generally.

4.6.1 Exempt User Scenario Consumptive Use Assumptions

The exempt use scenario assumes that the consumptive use percent for each exempt user is based on the historic use type. However, there is no guarantee that a future owner of a given surface water intake will have the same use type and therefore consumptive use fraction as the current. Therefore, this analysis may underestimate cumulative impact in any stream where the operator of an exempt intake makes changes to its operation that impact consumptive use. On the other hand, there is also that possibility that an intake could be transitioned to a less consumptive use type, thereby making the potential cumulative impact smaller.

Table 10: Data sources, number of intakes, and total potential demand used in the Exempt Demand scenario for permitted (*) and exempt intakes in non-tidal waters.

Stream Type	*Exemption Data Source Type*	*No. Intakes*	*Total (mgd)*
Non-Tidal	401 Certification	4	71
Non-Tidal	Intake Capacity	95	1558
Non-Tidal	Below Permit Threshold	882	74
Non-Tidal	Pre-1989	249	957
Non-Tidal	RFI 2009	65	4779
Non-Tidal	Safe Yield/1Q30	30	1774
Non-Tidal	VDH Capacity	45	503
Non-Tidal	VWP Permit	86	431

Table 11: Data sources, number of intakes, and total potential demand for permitted (*) and exempt intakes in tidal waters.

Stream Type	*Exemption Data Source Type*	*No. of Intakes*	*Total (mgd)*
Tidal	401 Certification	1	2260
Tidal	Intake Capacity	38	3708
Tidal	Below Permit Threshold	372	16
Tidal	Pre-1989	46	1955
Tidal	RFI 2009	39	981
Tidal	Safe Yield/1Q30	1	227
Tidal	VDH Capacity	7	107
Tidal	*VWP Permit	9	5

4.7 Modeling Withdrawals, Discharges and Consumptive Use

While the majority of surface water withdrawals are returned to streams and estuaries as point source discharges, a significant fraction leaves the system as irrigation, evaporationtranspiration, transmission losses, finished products from manufacturing, or human and livestock consumption. As previously mentioned, the portion of water that is not returned to the system is referred to as "Consumptive Use" (CU). This is an important variable in calculating a current and future water balance - and so how it is handled in a model warrants consideration.

The amount of consumption in Virginia ranges from between 1% to 100% depending on the use type and season. Summer CU is nearly twice that of CU in the winter (see Figure 22). Municipal withdrawals amount to approximately 60% of all non-power withdrawals in 2020 and are therefore responsible for much of the monthly variation and future growth in CU shown in Figure 22. Statewide monthly CU for all non-power uses is estimated as varying from between 200 to 400 MGD in 2020. The peak monthly CU is estimated to be nearly 500 MGD by 2040.

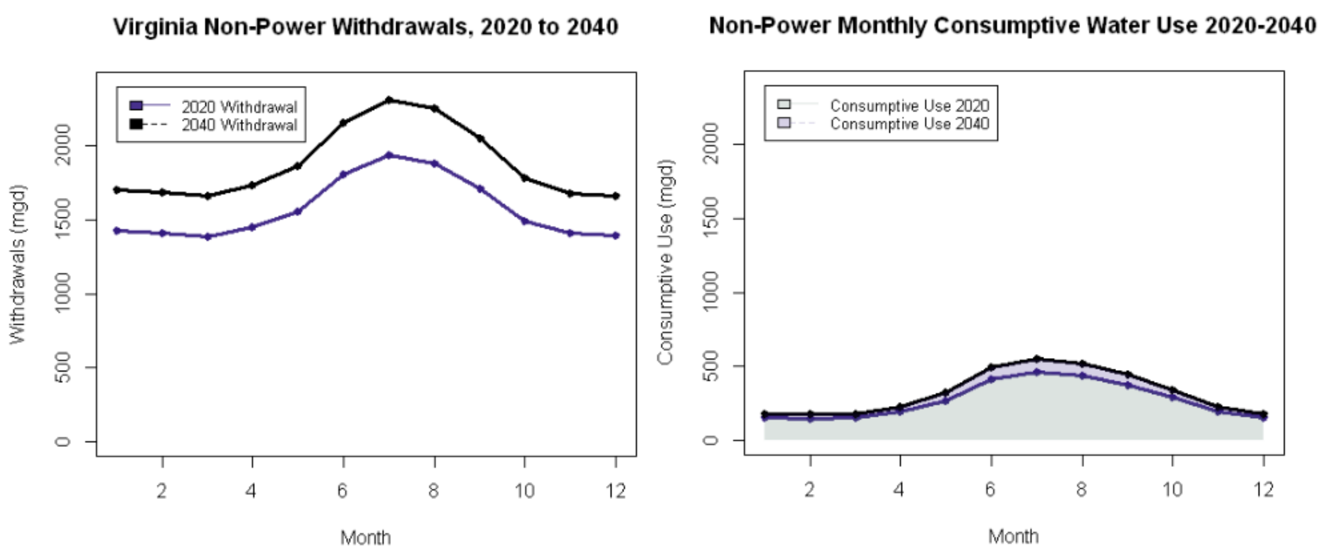


Figure 22: Average monthly simulated withdrawals (left) and consumptive use (right) for all uses except power generation. Simulated values for 2020 are based on a total annual demand of nearly 1,600 MGY, and 2040 are based on an annual demand of approximately 1,900 MGY.

4.7.1 Estimating Consumptive Use Factors

Throughout 2017-2019 DEQ collaborated with the Virginia Tech Department of Biological Systems Engineering through a USGS Water-Use Data and Research program (WUDR) grant on a project titled "Virginia's Consumptive Use Data Transfer, Export, and Analysis."[42] Primary results of this project include the development of a set of data retrieval tools to supply point source NPDES Discharge Monitoring Report (DMR) data to Virginia's VAHydro data system. By applying the tools developed through this project, DEQ was able to incorporate all reported point source discharges from Virginia and surrounding states into VAHydro.

Using this wealth of historic discharge data, CU factors (representing the fraction of a withdrawal that is considered consumptive) can be developed. CU factors are a critical component of the VAHydro model, and a necessary prerequisite for modeling future scenarios. By multiplying water demands (such as facility-level 2020 or 2040 demand) by a CU factor, the model is able to scale those demands to more accurately simulate the overall water balance of the

[42] McCarthy (2019), http://hdl.handle.net/10919/89928

stream system.

These percentages are calculated using several methods depending on data availability and use type. When reliable long-term withdrawal and discharge data is known for a given system, CU factors specific to that system are used. Most municipal systems are estimated by using the "winter base rate" method, provided that long term monthly withdrawal data is available. This method estimates summer time CU as the difference between summer and winter time demands (see 4.7.2). The remainder of systems were estimated based on analysis of NPDES data and comparison with CU values from scientific literature in the eastern United States. Because return flows are calculated as a function of the amount of water withdrawn, the resulting models can better represent seasonal trends in CU, the effects of addition or removal of facilities, and the ability to project changing point source flows based on changes in future demands. Table 12 shows the default values for the various categories in this analysis.

Table 12: Consumptive Use Factor Defaults

Sector Name	Factor Source	Factor
Agriculture	Literature median	100%
Irrigation	Literature median	100%
Aquaculture	VPDES Matched	0%
Industrial	Literature	10%
Commercial	Literature	10%
Energy	VPDES Median/Literature	2%
Municipal	Winter Base Rate	0-30% by month

4.7.2 Modeling Consumptive Use

The VAHydro model estimates the amount of water returned to the stream each day by subtracting the CU percent from the total daily withdrawal, then routing the return flow to the next downstream river segment unless an alternative return point is known. Because total annual, and monthly percent of annual demand is the same for each year for a given scenario, monthly CU does not vary from year to year within any given scenario. This may underestimate some increases in demand in dry years when drought restrictions are not in place, and overestimate CU during wetter years. Future analyses should include variations in demand based on meteorological factors to assess drought flow reductions due to CU occurring early in drought periods before restrictions are in place.

Location of Withdrawals and Return Flows

Most surface water withdrawn is used, treated and returned to the same river some miles downstream of the withdrawal. When the location of a return flow is known, models are configured to route return flow to the model river segment of the outfall location. When return flow locations are not known, return flows are modeled as returning to the stream in the next downstream watershed from the point of withdrawal (see Figure 23). Some systems (especially large municipal service areas) are structured such that discharge points are located in entirely different watersheds from their withdrawal. For example, the withdrawals in Spotyslvania County's Ni River Reservoir are used in the northern portions of that reservoir, and the majority of treated wastewater flows are returned to the tidal section of the Rappahannock River. DEQ's model is generally adjusted to simulate these effects where they are known to occur.

Low Flow Increases due to Withdrawals from Reservoirs and Groundwater

In general, CU should result in a net decrease in stream flows, with a greater decrease during times of drought due to the smaller baseline water budget. However, due to the use of "stored water", namely reservoirs and groundwater pumping, some streams will actually see an increase in low flows. This is because instead of pumping directly from streams during drought, water is withdrawn from reservoirs or groundwater wells, then returned to streams as a re-

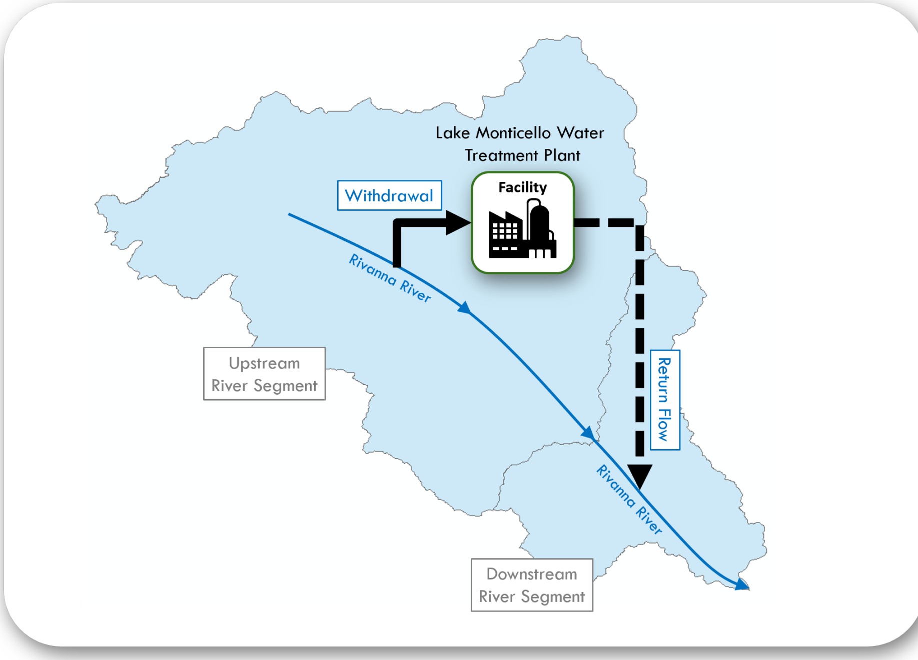


Figure 23: Default location of return flows from municipal wastewater treatment.

sult of the wastewater treatment process. Not all groundwater pumping is assumed to be returned to the stream. Groundwater withdrawals are only assumed to be returned to streams if they are a) part of a conjunctive system with surface water intakes, or b) part of a municipal system with total groundwater withdrawals > 100 MG in a single year. Domestic private well withdrawals (Small Self-Supplied Users) are assumed to be treated on-site (septic), and therefore do not add or subtract from the stream water balance.

Consumptive Use for Power Plant Cooling

Power plants without historical data are assumed to have a CU percentage of 2%, based on the median value from the 2018 VPDES study. Despite a 2020 average daily demand of approximately 3,000 MGD (3 billion gallons per day) in Virginia's nontidal rivers (including power plants in the WV and MD parts of the Potomac), evaporative losses from cooling amount to less than 100 mgd in total CU.

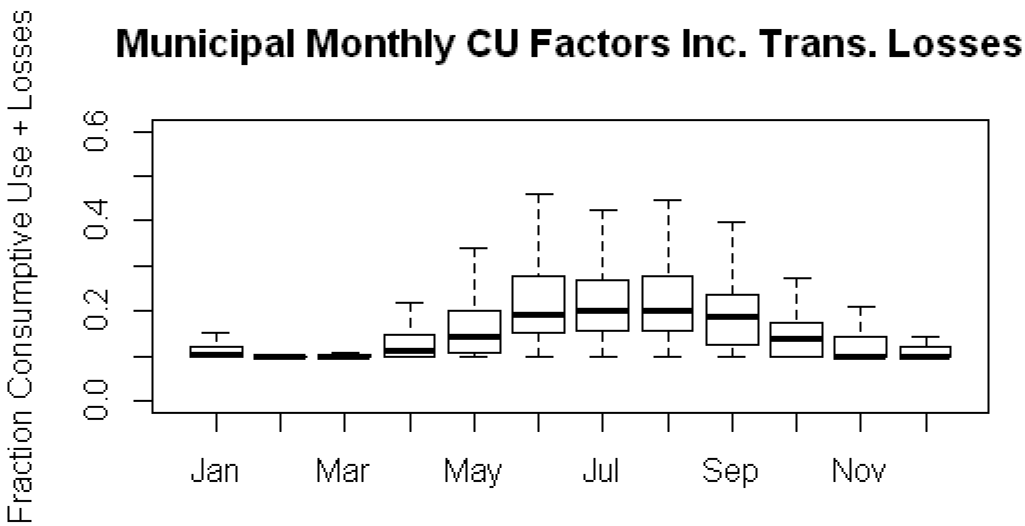
Municipal Withdrawals Using Winter Base Rate Method

Where possible, CU for public water supply withdrawals with long-term records are estimated using a variation on the "winter base rate method" [Ducnuigeen et al., 2015]; [Li et al., 2017], plus a standard factor for transmission losses (10%, see 4.7.3). This method relies upon the assumption that outside watering activities are minimal during the winter, which is a valid assumption throughout Virginia. However, in some areas where winter demands are higher than summer, therefore the WBR is not applicable. For those systems, we used the "Standard Municipal Distribution" given below. Figure 24 shows the range of consumptive use fractions/percentages, which are as low as 0.1 (10%) during winter months, and as high as 0.4 (40%) during summer months in a small subset of systems.

- "Standard Municipal Distribution": CWS systems with seasonal populations or large industrial users are estimated with a standard municipal distribution, based on the "winter base rate method" for Virginia as a whole.

- *In the Potomac River basin outside of Virginia* an analysis of CU was performed by ICPRB. Demands in West Virginia, Maryland, and Pennsylvania were compiled by ICPRB, with CU factors that were obtained from a combination of site-specific (where available), and literature factors (see [Ahmed and Seck, 2020]).

Figure 24: Summary of estimated consumptive use fractions for all municipal facilities where the Winter Base Rate method could be applied. Median values ranged from 0.1 (10%) to 0.2 (20%) in the summer, with summer-time evaporative losses as high as 0.4 (40%) in some areas.



4.7.3 Transmission Losses

Municipal water systems deliver water to service areas through a large network of pipes (the distribution system) of varying age and condition, and then water is returned through another network of conveyances to the wastewater treatment facilities (the collection system). Consequently there can be a wide range of transmissions losses, or "leakage from pipes during water transmission". Transmission losses may be permanently lost via evapotranspiration, they may return to the stream as base flow, or they may be delayed and effectively lost from the short term water budget. However, estimating the amount that is permanently lost is very difficult, and can vary seasonally and annually within the same system. This model used a value of 10% to represent the percent of water withdrawn and not returned to the stream due to transmission losses for all systems. Improved quantification of the fate and magnitude of transmission losses in water-stressed watersheds should be prioritized in future planning efforts (more on this can be found in Appendix C.3).