Chapter 5 Assessing the Long Term Sustainability of Water Resources

Introduction to Cumulative Impact Analysis

This Chapter contains an analysis which describes the expected cumulative impacts of future water demands on streamflows to assure the long-term sustainability of Virginia's water resources. Sustainability is defined in terms of maintaining the "beneficial uses" that are considered to be essential to the wellbeing of the Commonwealth's human and natural resources. These beneficial uses are protected by law, defined earlier in this SWRP, and include the protection of fish and wildlife habitat, maintenance of waste assimilation, recreation, navigation, cultural and aesthetic values, public water supply, agricultural uses, electric power generation, and commercial and industrial uses. The various beneficial uses are termed as such because they literally "use" water; however, the ways in which they use the water are varied. Beneficial uses which involve the pumping of water from the stream are considered "off-stream" uses, whereas uses such as recreation, waste assimilation, and aquatic life are considered "in-stream" uses. Different beneficial uses may require water in differing amounts, at different times, and of varying levels of quality. Nearly all uses have a specific set of conditions during which they are most vulnerable to flow alterations. This set of conditions during which a use is considered most vulnerable is referred to as a use's "critical condition." The potential for changes to streamflow under these critical conditions are described as "flow alterations." This analysis produces an assessment of risk to various beneficial uses resulting from alterations to critical flows induced by water supply activity.

Drought as Critical Condition

Although Virginia is generally considered to be a "water rich" state, the Commonwealth still faces infrequent but severe periods of water scarcity that prove stressful to both in-stream and off-stream beneficial uses. These periods of scarcity have their roots in the variations in seasonal and intra-annual meteorology that characterize the climate, as well as the need to rely on surface water to supply a substantial portion of annual water needs. During years with normal to high precipitation, Virginia's net water withdrawal from surface water in non-tidal streams is less than 5% of the median daily streamflow. However, due to seasonal and annual variation in flows, average demands make up an estimated 30% of the total mean flow in Virginia streams during September Drought Warning conditions, further described below. Figure 5-1 shows a map of projected increases in surface water demand for 327 non-tidal river segments simulated for this analysis. This map illustrates the large spatial variation in surface water demands, which results in an unequal distribution of impacts to Virginia's riverine system. This distribution results in some stream segments that are virtually untouched by the human water supply system, and others whose off-stream demand exceeds 100% of flows during periods of drought. During these times of drought, off-stream water demands rely largely on water stored in reservoirs and groundwater sources. Surface flows during this time are dominated by point source returns in many streams, linking the quantity and water quality of downstream flows with those point sources.

Flow Metrics to Describe Risk to Critical Conditions

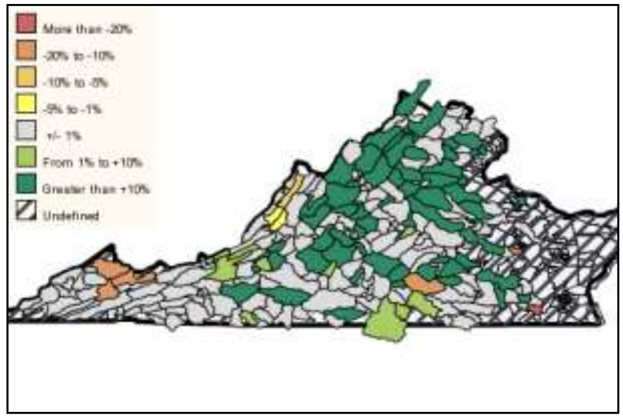

Figure 5-1: Map of the projected change in daily withdrawal from surface waters in non-tidal watersheds in the Commonwealth of Virginia.

By integrating the locality-based predictions of future water demand with a process-based model of in-stream flows, this analysis characterizes the probable spatial distribution and likely extent of impacts to the full range of in-stream and off-stream beneficial uses. The increased demands projected by the year 2040 will result in a net decrease in streamflows as a result of consumptive uses and additional stress upon all beneficial uses. The most common critical conditions for beneficial uses in Virginia are periods of low flow, or drought. Therefore, a majority of the metrics selected for analysis will focus on these low flows. Because certain recreational uses require high flows and a growing realization of the positive effects of some storm flows on water quality in the riverine system, analysis was also performed to quantify the potential for reduction of high flows. Overall, four metrics were selected to characterize the extent to which future demands will affect the various critical conditions and beneficial uses in Virginia streams. Table 5-1 has a brief overview of these metrics. A full description of metrics can be found below in the section entitled "Method II: Metrics for Cumulative Impact Analysis." The thresholds chosen for significant impacts are intended to be "screening thresholds" and are intentionally conservative. They are not a prediction of certain negative impacts, but rather an indication of a potential future impact deserving of greater scrutiny and planning.

Metric Name	Metric Purpose and Description	Screening Threshold
Changes in August Low Flow (ALF)	Watersheds that see substantial changes to ALF will face an increased probability of aquatic life impacts.	Decrease in ALF >=10%
Changes in 7Q10	Areas that suffer decreases in 7Q10 flows will have decreased estimated waste assimilative capacity as well as flows for off-stream uses.	Decrease in 7Q10>=5%
Withdrawals as percentage of September Drought Warning Flows	This measurement is an indicator of cumulative water supply system stress and indicates either substantial decrease in streamflows or reliance on stored water. Streams with withdrawals as a high percent of baseline drought warning flows are considered to have elevated risk of algal blooms due to storm flow capture and/or risk of water scarcity.	Withdrawal >=25% September Warning Flow
Changes in Drought of Record Flow	Drought of Record (DoR) flows are the ultimate limiting factor in safe yield. This estimates the change in flow under DoR meteorological conditions and 2040 projected demands.	Decrease in DoR Flow >5%

Table 5-1: Cumulative Impact Analysis indicators used in the 2014 SWRP; indicators reflect impacts on infrastructure, downstream uses, aquatic life, and assimilative capacity due to increased water use

Method I: Cumulative Impact Modeling

Modeling Objectives, Time-Scale, and Components

The ultimate goal of this modeling exercise was to be able to predict the approximate location, direction, and magnitude of impacts to the in-stream and off-stream water system from increasing water demand and water supply system management actions. The various beneficial uses that are identified in this analysis are impacted by flow variations on an annual, seasonal, and even daily time scale. Therefore, the model analyzed the cumulative impacts capable of simulating the water balance on a daily basis, as well as simulated the variation in conditions expected to occur on a seasonal and annual basis. The baseline flow budget can be greatly altered by the management of reservoirs, withdrawals, and point source discharges. Therefore, a suitable modeling system must be capable of simulating the flow altering effects of the sometimes complicated rule sets that govern these water supply activities. This requires a basic simulation of streamflows, including these fundamental components:

- A baseline flow time series – an estimate of the water entering the riverine system on a daily basis over a “representative” time period. A “representative” time period is generally considered to be one that shows the full range of seasonal and annual climatic variations including “average” years, “wet” years, and “drought” years.
- An inventory of current water withdrawals and discharges and a projection of future water withdrawals and discharges.
- A simulation of operational rules for water supply entities (withdrawals, reservoirs) with known operational triggers.

- Major reservoirs - Minimum flow releases were simulated for major reservoirs where operational rules were known. Operational rules for this simulation came from previously simulated VWP modeling evaluations and from information gathered during the water supply planning process.

Understanding the Water Budget

To understand the extent to which activities produce flow alterations, an assessment of basic components of the flow budget (natural inflows, withdrawals, and discharges) must occur, as well as a perception of the natural variability that exists in the riverine system. These basic components are then represented in a water supply system model that helps quantify the relative effects of complex management actions on the system. Once the means to quantify the basic driving forces of the water budget is developed, the assessment of flow alteration can occur.

Baseline Flow Budget

A critical tool in water supply management is the construction of what is often referred to as a "baseline flow budget." This budget is estimated by constructing a model of the flows through a river system *without* including withdrawals, discharges, or detainment of water by lakes or reservoirs. By considering the quantity, quality, and timing of flows into and through a river system, the baseline budget allows for the determination of total capacity, assessment of system stress due to water supply activities, and setting reasonable expectations for potential beneficial uses. In sum, the baseline flow budget allows for the creation of an accurate accounting of the ways a current or future beneficial use alters the quantity, quality, and timing of water flows throughout the system.

A baseline flow regime can also be used to set reasonable expectations of the beneficial uses that can be maintained in the watershed. For example, the baseline flow regime identifies the total water budget that is available for sharing amongst the beneficial uses during drought. By comparing a stream's baseline drought flow values to the total water demand in the stream, a sense of the stress imposed on the stream and/or water supply system can be determined. If a stream's demands are equal to a high percentage of its baseline flow at any time, this means that either downstream beneficial uses will see flow reductions, reservoir storage will be depleted, or off-stream demands must temporarily decrease due to conservation restrictions. Baseline flows can also be used to determine recreational potential since it would be unrealistic to expect that a slow moving Coastal Plain stream could be managed to produce frequent, high quality whitewater rafting flows. Similarly, a small, flashy mountain stream whose summer flows slow to a trickle would be hard pressed to meet the demands of a large community water system without a large storage reservoir to supplement demands during drought. In short, the baseline flow regime shows how much water can potentially flow into a reservoir during drought, the native flow conditions for aquatic organisms, the potential for recreational uses such as boating and rafting, and the potential variation in in-stream flows during wet and dry months, and normal and drought conditions.

In order to establish a baseline flow budget, a hydrologic model is employed to provide a simulation of rainfall, runoff, percolation into groundwater tables, and flow into streams.

Rainfall-Runoff Model Scale, Scope, and Accuracy

When attempting to quantify the status of a water supply system, the various components that play a role in governing water availability in the system must be identified, and the initial water budget that the system has to work within must be quantified. Rainfall-runoff models can be very useful tools in this endeavor since they allow the piecing together of the various elements in a way that shows the influence of the various impoundments, withdrawals, and discharges. Rainfall-runoff models also allow the quantification of the effects of reservoirs in evaporation. The baseline runoff flow and sub-watershed units used for simulation and analysis in this study came from a decision support system referred to as VAHydro.

VAHydro simulates complex reservoir and withdrawal operational rules, a physically-based channel routing methodology, and has a surface water hydrology and hydrography component built on the hydrologic framework established in the development of the Phase 5.3 Chesapeake Bay Watershed Model (CBP5), which was expanded to include areas of Virginia outside of the Chesapeake Bay watershed. The CBP5 model runs on an hourly time step (15 minutes in some areas), and has a 21-year simulation time period from 1984 to 2005, which is considered to adequately represent the range of meteorological conditions common to Virginia. This model was calibrated using flows from over 140 continuous flow gages and produces flows for 327 non-tidal stream reaches in Virginia. The only streams that are not modeled are those that are subject to significant tidal influence. While the un-modeled tidal streams represent a significant portion of the Commonwealth's total area, water use in these areas is predominantly from groundwater sources, whose cumulative impacts are assessed in the Virginia Coastal Plain Model of groundwater aquifer pumping. Figure 5-2 shows a map of the VAHydro sub-watersheds modeled during this analysis.

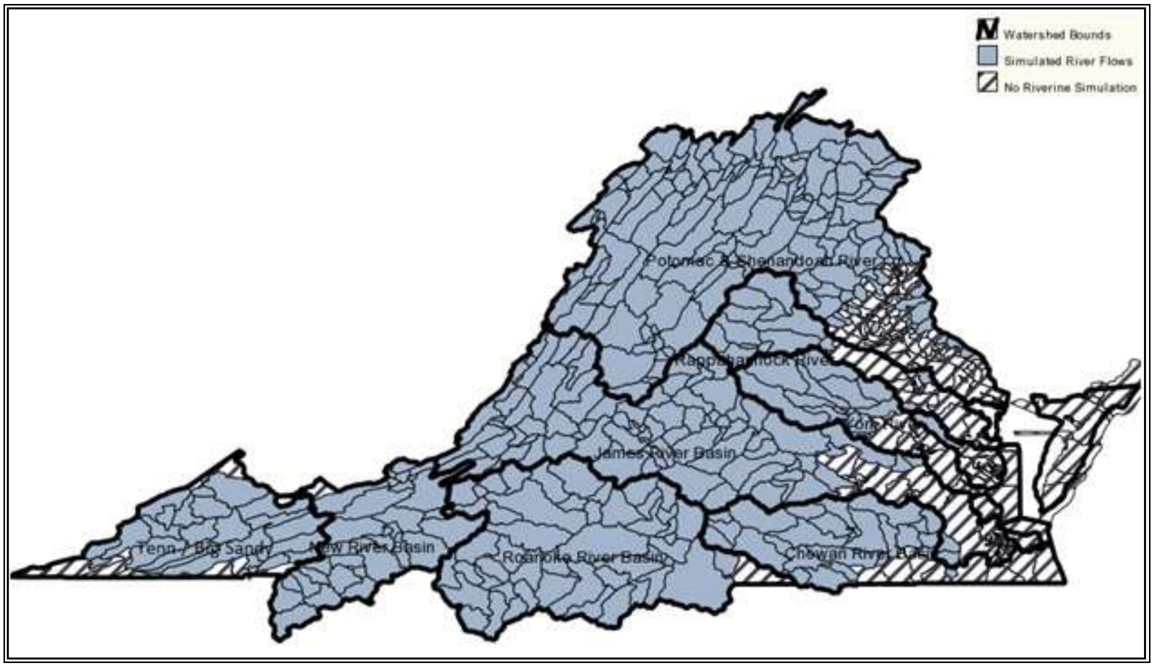

Figure 5-2: A map of the extent of the VAHydro rainfall-runoff model for simulation of the cumulative impacts of current and future water supply actions; cross-hatched areas are not simulated because of significant tidal influence or drain outside of Commonwealth boundaries

The CBP5 model was reviewed by DEQ in 2006 and determined to have a reasonable level of accuracy for total water budget: 82.9% of the 141 gaged streams were within 15% of total annual measured flows for a 16-year calibration/validation period, and 92.2% were within 20%. Of the largest 50% of basins, the results show 90.1% of modeled flows within 15%, and 97.2% within 20%. Reasons for hydrologic model error can be the result of simplifications in the modeled processes, errors in data input, and errors in the observed values of flow gages when estimating flow rates outside of the gages observed record. Sources of error in the CBP5 model may be the result of errors in the VWWR Regulation water withdrawal records, which suffered from gaps early in the record; precipitation variations; and failure of the assumption that groundwater boundaries conform to surface water boundaries (both of which become increasingly important in smaller basins).

For an investigation such as this, absolute model error is less critical than understanding the general direction of changes. By calculating the difference between current conditions and projected future conditions, model errors may impact the magnitude of predicted flow changes, but they will not affect the direction of those flow changes. For example, in a stream reach that is expected to see increased consumptive demands from direct withdrawals, seasonal low flows will decrease, and the numerical models used for this analysis will never predict an increase.

Data Sources and Assumptions

The water supply planning data set contains estimates of the water use in Virginia based on data gathered during Virginia's water supply planning effort. The values given in this dataset reflect the best assessments of water use as of 2010 and projected water use in the year 2040. The rates of current and future water withdrawal in this dataset are based entirely on data submitted to DEQ in the local and regional water supply plans and represent a more comprehensive picture of water supply activities in Virginia than has ever been assembled. Nevertheless, sources of uncertainty exist, most important of which are as follows:

- Monthly variation – 37% of systems included monthly variation information. Monthly use patterns can also vary considerably from year to year within a given system, especially in the case of CWS water withdrawals. Given this uncertainty, monthly variation was not considered in this simulation.
- Water withdrawal magnitude - Water withdrawals were estimated based on the data submitted during the water supply planning process from every locality in the Commonwealth. Demands in the Potomac River Basin outside of Virginia were obtained from estimates developed during the 2009 Middle Potomac River Watershed Assessment. Current and projected demands for areas in the Dan River in North Carolina were obtained from the North Carolina water supply planning website.
- Water withdrawal location – The WSP Regulation did not require the submission of precise location information for withdrawals. However, many of the systems report under the VWWR Regulation (VWUDS database), and significant efforts were made to link the location of these systems to entries in the VWUDS database for the purpose of more accurate spatial scale for simulation and analysis purposes. Locations of systems for which no VWUDS linkage was established were located according to the reported locality, or if lacking locality information, they were located at the center of their planning region. Overall, DEQ established links to the VWUDS database for 922 out of 2,836 water supply systems, roughly 33% of systems.
- Point source flows – Point source data was not required by the WSP Regulation, so estimates were made based on the VPDES database, with monthly varying flows based on the average reported discharge values from the years 2005-2009. Consumptive use fractions for future withdrawals are an area of high uncertainty. When looking at a small basin scale, water is often withdrawn from one stream only to be returned via point source discharge in another stream nearby. For areas of the Potomac River outside of Virginia, point source estimates developed during the 2009 Middle Potomac River Watershed Assessment were used. No point sources discharges were simulated for areas of the Dan River in North Carolina.

Consumptive Use Definition and Assumptions

"Consumptive use" describes the net loss of water from the riverine system as a result of evaporative losses due to off-stream use or due to detention in in-stream impoundments. The water removed from streams for off-stream uses is divided into a "consumptive" and "non-consumptive" fraction. The "non-consumptive fraction" is the portion of withdrawal that is returned to the stream via a point source discharge. An evaporative loss, or "consumptive use fraction," is that portion of a withdrawal that is not returned to the stream. One of the main objectives of this analysis and water supply planning process is to ensure against future water shortages and unforeseen negative impacts to in-stream beneficial uses. For this reason, it is important to make assumptions about consumptive use that are conservative, erring on the side of assuming a higher level of net consumption from water use activities. Because of the uncertainty in both consumptive use and monthly use pattern variation, no increase in point source discharge is modeled, but the mean reported rate of discharge was used, varying by month, for the years 2005-2009. This assumption will likely result in an underestimation of future discharges. Future withdrawals, on the other hand, were modeled without monthly variation due to the inconsistency in reporting of monthly variation amongst the water supply systems. This will have the effect of likely underestimating summertime withdrawals, particularly in July and August. The result of underestimating both point source discharges and withdrawals will result in a conservative estimate of flow reduction, but will preserve the spatial distribution of expected flow alterations.

Major Reservoirs under Construction or with New Operational Rules

Given that water supply infrastructure development and permitting changes are constantly under way, it can be challenging to select a point in time that represents "current" conditions. Major reservoirs have the greatest potential to make immediate changes to surface water hydrology. The following criteria were used to determine whether or not to model the presence of a new major water supply impoundment or major alteration to the management of an existing impoundment.

- Projects that have VWP permits issued as of fall 2013, but that have not yet been constructed, were not modeled as part of "Current Condition" model runs. These projects were included in "Projected 2040" model runs, allowing more understanding to the changes due to demand, as well as due to currently approved strategies to meet that demand.
- Projects with newly issued or re-issued VWP permits between winter 2010 and fall 2013 that require no change in infrastructure for operation were modeled in both current and projected 2040 scenarios.

Method II: Metrics for Cumulative Impact Analysis

Flow Statistics and Metrics

A common method in hydrologic analysis is the use of the "flow statistic" – a statistical calculation of the magnitude of flow that occurs at a specific frequency at a certain time of year. The Commonwealth's drought flow indicators are one example of flow statistics.[60] Water quality programs, such as the VPDES, also use flow statistics to characterize the capacity of a stream to assimilate waste products. Aquatic biologists also use flow metrics to describe critical conditions for living organisms in streams. For a study of the impacts of changes to water supply needs, it is important to select flows that are known to be readily impacted by common water supply activities. These flow statistics are used to characterize current and projected future streamflows as a result of water supply activities. The potential impacts of future water supply needs are estimated by calculating the percent change between current and future flow conditions as described by these flow statistics. The percent change that results is described as a "flow alteration metric" for this study.

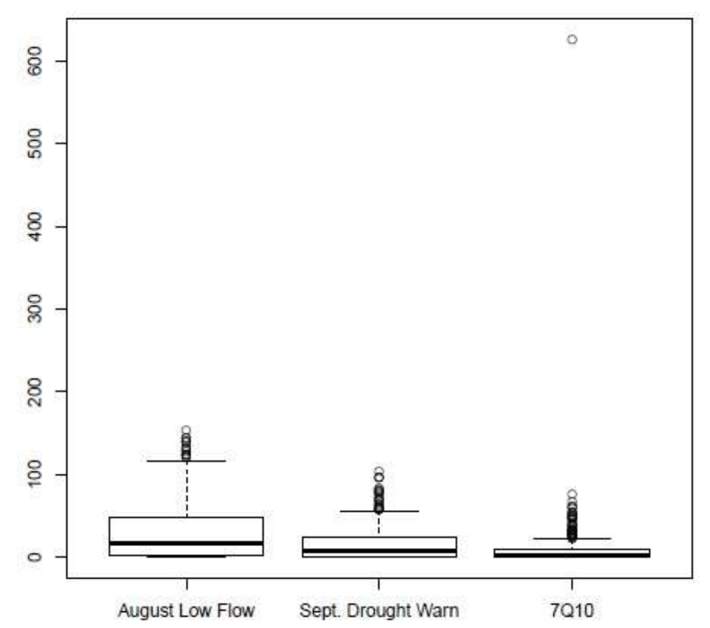

Figure 5-3: Box and whisker plot of the three flow statistics selected for this SWRP. These plots show relationships between the median, standard deviation, and outliers for small to medium sized streams within the Commonwealth.

To address the critical condition most susceptible to water supply management decisions, this study calculated a variety of alteration metrics based on the following three flow statistics which represent three separate beneficial uses:

- August Low Flow (ALF) – An indicator of the biological system carrying capacity as influenced by minimum flow volumes. ALF values tend to describe a moderately dry condition that falls outside of the drought ranges specified by the Virginia drought flow thresholds and are the highest flow statistics considered in this study (see Figure 5-3).
- September Drought Warning – The drought flows associated with voluntary water restrictions in the Virginia Drought Assessment and Response Plan.[61] September drought warning flows describe a condition of moderate drought, with a median value that falls in between the ALF and 7Q10 values found in Virginia streams (see Figure 5-3).

[60] http://www.deq.virginia.gov/Programs/Water/WaterSupplyWaterQuantity/Drought/DroughtMonitoring.aspx
[61] http://www.deq.virginia.gov/Portals/0/DEQ/Water/WaterResources/vadroughtresponseplan.pdf

- 7Q10 – A common flow metric used to establish point source discharge limits. This statistic describes a flow condition that is expected to occur only one time in a 10-year period, and is the lowest flow statistic used in this analysis, with the exception of the drought of record flow (see Figure 5-3).

In addition to these three basic flow statistics, an additional numerical indicator was developed to characterize the potential change to streamflows during a repeat of the meteorological conditions during the historical drought of record. The 2002 drought was the drought of record for a majority of the Commonwealth, and the month of September was the lowest flow month during this period. Therefore, the simulated mean daily flow for the month of September was selected as the Drought of Record (DoR) flow indicator for this analysis. Models were run to simulate the mean daily September flows that would result from 2002 meteorological conditions and current consumptive withdrawal values with projected 2040 consumptive withdrawal values. The percentage differences in streamflow between those two consumptive withdrawal scenarios was calculated as a representation of the potential for changes in future water supply demand to exacerbate the most critical drought flow conditions in the future.

This choice of flow statistics provides benefit beyond the specific beneficial use that they represent. They also describe a full range of the months (July through October), and flow ranges (moderately dry to extreme drought) that define the critical conditions common to a majority of beneficial uses. The calculation of flow-alteration metrics from these basic flow statistics are described in detail in Table 5-2.

Metric Name	Metric Purpose and Description
Change in August Low Flow (ALF)	Watersheds that see substantial changes to ALF will face an increased probability of aquatic life impacts. The potential for these impacts will present a challenge for the issuance of new or expanded withdrawal permits and may benefit from investment in increased biological monitoring to determine the real impacts at higher levels of flow alteration. While increased reservoir storage is one option to consider in alleviating these impacts, it is often difficult to maintain higher August releases and flow-bys given that the most significant droughts last through September and into October. Only reservoirs with very large amounts of storage relative to demand are able to sustain off-stream needs without reducing flows in the early months of drought. Stream segments with greater than a 10% reduction in ALF were considered to be of high risk.
Change in 7Q10 (7Q10)	Areas that suffer decreases in 7Q10 flows will face choices that involve reducing consumptive demands, increasing reliance on stored water during dry periods, or reducing the amount of

	waste discharged from point sources. These choices will involve weighing the cost-benefit associated with upgrading wastewater treatment equipment, water supply infrastructure, and creation and/or enforcement of drought ordinances. Because 7Q10 is a low flow that tends to occur in late September and early October, decreases in 7Q10 have implications for water supply operations. Stream segments whose 7Q10 decrease due to increased consumptive withdrawals are considered to be at risk for more severe drought impacts and should engage in a more in-depth analysis of non-permitted water users' capabilities and best practices. Stream segments with greater than a 5% reduction in 7Q10 were considered to be of high-risk.
Withdrawals as Percentage of September Drought Warning Flows (W9W)	This measurement is an indicator of cumulative water supply system stress. Because it is evaluated as a function of the baseline flow budget on a watershed basis, it is one of the best indicators of areas requiring collaborative solutions. It shows the potential for conflict amongst different off-stream uses, as well as the potential for impacts to in-stream beneficial uses. On- and off-stream storage reservoirs may be used to ease demand pressures during drought by capturing flows during high flow periods (summer and fall storms, winter and spring base flows). However, due to the growing realization of the role of storm flows in maintaining water quality and healthy aquatic communities, this approach may ultimately lead to the need for increased biological monitoring and investment in infrastructure needed to develop complex operational management tools and intra-system cooperative agreements. Streams with a high W9W are considered as having a heightened risk of algal blooms due to storm flow capture, as well as having a risk of water scarcity for off-stream uses. Stream segments with greater than a 25% W9W were considered to be of high-risk.
Changes in Drought of Record (DoR) Flow	DoR flows are the ultimate limiting factor in safe yield. This estimates the change in flow under DoR meteorological conditions and 2040 projected demands. Safe yields of withdrawals and reservoirs are directly impacted by reductions to the DoR flow; therefore, even small changes to the DoR flow are considered to be of critical concern. For this reason, river segments with greater than 5% reduction in DoR flow were considered to be of high-risk.

Table 5-2: The "flow metrics" used in this SWRP to indicate risk of negative impact to beneficial uses from flow alteration caused by cumulative water supply activities

Modeling, Characterizing Uncertainty and Managing Risk

Risk management is defined as "quantifying the effect of uncertainty on objectives."   Given the considerable uncertainties in a forward projection exercise, it is extremely important to characterize the sources of uncertainty and the potential magnitude of uncertainty as accurately as possible. It is also important to identify strategies for managing that risk and responding to those uncertainties. In water supply projection, the greatest sources of uncertainty are those that are not subject to any form of regulation, such as population growth, economic development, geographic distribution of growth, and climatic variation. The regulated uncertainties, such as the acceptable level of alteration in a given stream, will all be bounded by the unregulated uncertainties in this case. For example, a regulation that requires no more than 20% decrease in ALF would be of concern only in areas where there was a high probability of demands growing beyond a certain finite level.

The effects due to uncertainties in geographic distribution can be analyzed by using a probabilistic approach to quantifying model results. By looking at the range of values of impacts that are predicted as a function of the given water supply plan projections, a sense of the range of predictions can be determined. An assumption can be made that some projections will fall short, and some will be exceeded by the actual growth in water supply demand that occurs by 2040.   In other words, if the assumption is made that errors in prediction are randomly distributed in a normal, or "bell curve" shape, then the median predicted demand increase is a good estimate of the median demand change that will occur in 2040. If this assumption is true, then a prediction can be made that overall the median predicted flow alteration may represent a good estimate of the level of risk to streams in a given area.

Projection Uncertainty and Operational Rules

There are several sources of uncertainty in predicting the cumulative impacts to in-stream flows as a result of future water supply system change. The most common in this analysis are as follows:

- Projecting demand magnitude - Demand projections in the Commonwealth are highly linked to population growth; therefore, if population growth is greater or lesser than projected, demands will likewise be greater or lesser.
- Geographical distribution of growth - Localities used their best judgment as to where it was believed that future growth would be likely; however, it is believed that there could be considerable differences in the actual geographic distribution of new water demands. If demands occur in different watersheds than currently predicted, the source of the water needed to meet those demands will be expected to change as well.
- Operational uncertainty - Water withdrawals and reservoir operations may vary widely from day to day and season to season. Also, the level of knowledge of these operations differs widely depending

on the water system's permit status. There is a very strong understanding and ability to simulate the operations of systems that are covered by a VWP permit, 401 Certification, or some known voluntary management rule set (see Chapter 2, Virginia's Collaborative Management Framework). For other grandfathered or exempt operations, knowledge of these operations is incomplete. While the larger withdrawals fall into the category of known operations, in areas with a large number of small unknown operations could potentially result in significant model error.

For these reasons, the expected impacts will be examined as indicating a greater or lesser probability of some negative impact, rather than as an absolute prediction of an impact. While considering the streams with the greatest potential for impacts, statistical descriptions such as Median Projected Impact over a group of streams will be examined. The median impact over a group of streams will possibly represent a more likely consequence of the projected growth in demand, since the permitting process tends to encourage distributing demands to less impacted areas in order to minimize the incidence of high levels of degradation. Areas that are predicted to have either a large potential for demand growth or large potential for beneficial use impacts should be evaluated further, with emphasis placed on obtaining greater level of detail for operations as well as limits to growth.

To understand the extent to which activities produce flow alterations, an assessment of basic components of the flow budget (natural inflows, withdrawals, and discharges) must occur and understanding the natural variability that exists in the riverine system. These basic components are then represented in a water supply system model that allows the quantification of the relative effects of complex management actions on the system.

Annual and Monthly Flow Variability

Streamflows in Virginia are highly variable due to the substantial variation in rainfall (see Chapter 3, Virginia's Environmental Resources for a discussion of Virginia climate). There are significant variations from year to year and from month to month within a single year. For example, in the Big Otter River near Evington, Virginia, mean daily streamflows varied from a low of 67 cubic feet per second (cfs) in 2002 to a high of 570 cfs in 1987, a difference of over 900% (see Figure 5-4 for annual flow rates for this gage from 1984-2005). Streamflows also vary from month to month as a result of differences in evaporation and transpiration, with the highest streamflows usually occurring in cooler winter and spring months, and the driest months occurring when temperatures are highest in the summer and early fall. Figure 5-5 shows an example of this variation, in the Big Otter River at Evington Virginia. At this gage, the month with the highest median flow (March, 372 cfs) has more than three times the flow than the lowest flow month (September, 103 cfs). In addition to these temperature-driven variations, streams in Virginia can see some of their highest flows as a result of hurricanes in the late summer and early fall months. The years with high temperatures, low winter rainfall, and little to no tropical storm/hurricane activity produce the most severe droughts. Because of these wide variations in flows, planners, engineers, and permitting agencies commonly focus on the driest years and months when determining the amount of water that is available for withdrawal from streams.

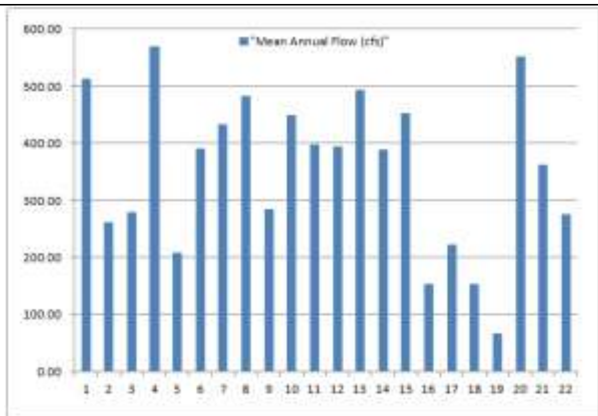

Figure 5-4: Observed average daily streamflows by year in the Big Otter River near Evington VA (USGS 02061500) from 1984-2005. This period saw a low of 67 cfs, an average of 354 cfs and a high of 570 cfs

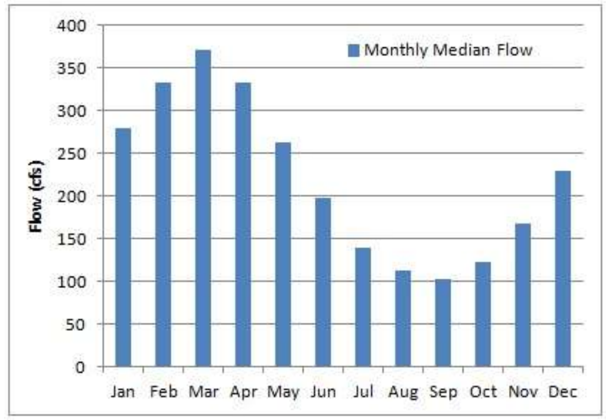

Figure 5-5: Observed median daily baseline streamflows by month in the Big Otter River near Evington VA from 1936-2013

Quantifying Hydrologic Drought

As a result of the severe drought in 1999-2002, the Commonwealth developed a set of measurements to define the occurrence and severity of drought conditions. The measurements used for this drought designation are based on rainfall, groundwater well levels, soil moisture, and streamflows. While the water supply activities that are covered in this SWRP cannot affect rainfall and soil moisture, they can have a substantial impact on both streamflows and groundwater well levels. Drought that is associated with only streamflows and groundwater levels is often referred to as "hydrologic drought." Because of the limitations of Virginia's current groundwater monitoring and modeling tools, and because streamflows are generally more sensitive to short-term changes than groundwater levels, this discussion is limited to those drought indicators that pertain to streamflows.

It is common to characterize the relative "dryness" or "wetness" of a stream according to its ranking relative to all other flows that have ever been recorded in that stream. This ranking formula is known as a "non-exceedance percentile," which literally answers the question "what percentage of flow measurement that has been taken at this location that is LESS than the current value?" In Virginia, a stream's drought status is considered to be either "Normal," "Drought Watch," "Drought Warning," or "Drought Emergency" based on a monthly "non-exceedance percentile." This ranks a given daily flow against all other flows that have been recorded at the site in a given month. Based on where a given daily flow reading is ranked in this table, the stream's drought status is determined as follows:

- Normal (>25%) - When streamflows in a given month are ranked at or above the 25th percentile, that gage is said to be in "normal" conditions.
- Watch (between 10-25%) - When the stream gage reads between the 10th and 25th percentile, the stream is said to be in a state of "drought watch."
- Warning (between %) - When the stream gage reads between the 5th and 10th percentile, the stream is said to be in a state of "drought warning."
- Emergency (less than 5%) - When the stream gage reads less than the 5th percentile, the stream is said to be in a state of "drought emergency."

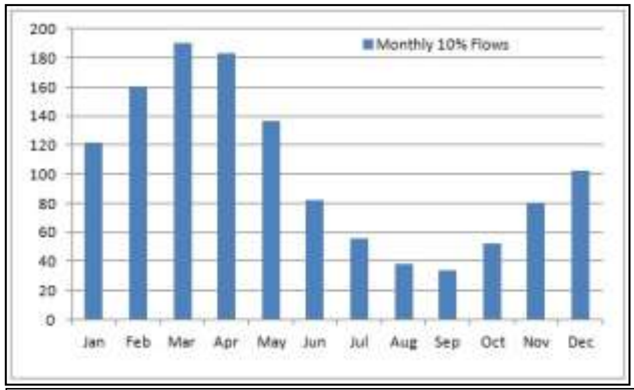

Figure 5-6: Observed monthly 10 percent non-exceedance flows average streamflows in the Big Otter River at Evington VA (USGS 02061500); the 10 percent flows correspond to a "drought watch" status according to the Virginia statewide drought indicators

For an example of "Drought Warning" flow levels, Figure 5-6 shows a plot of the monthly 10% flows in the Big Otter River. Based on this chart, in the month of August, an observed flow that is less than 38 cfs is considered to be below the 10th percentile, and, therefore, is categorized as a drought warning flow. Table 5-3 shows the full range of monthly historical flow non-exceedance percentiles for this same stream gage for all months of the year.

	Min	5%	10%	25%	50%	75%	90%	95%	Max
January	57	105	122	189	280	436	725	1,060	11,700
February	78	137	160	218	333	518	802	1,140	8,140
March	75	165	190	260	372	563	898	1,320	10,700
April	81	159	183	231	333	502	792	1,080	10,700
May	52	116	137	183	263	391	598	873	12,400
June	11	66	82	128	197	281	477	729	35,700
July	4.2	41	56	86	140	211	370	546	6,440
August	0.75	27	38	63	112	189	349	589	12,400
September	0.64	25	34	59	103	170	318	549	20,200
October	8.4	36	52	78.5	122	199	348	615	12,700
November	28	67	80	112	167	271	478	704	12,400
December	42	84	102	143	230	356	613	913	9,700

Table 5-3: Observed annual average streamflow in the Big Otter River at Evington VA (USGS 02061500) from 1984-2005; flow values for 5th, 10th and 25th percentile correspond to the drought Watch, Warning, and Emergency thresholds for a given month

Flow Alteration

In general, anything that affects the quantity, quality, or timing of streamflows can be said to be a "flow alteration." Flow alterations due to human activities are understood to varying degrees. The most common and powerful flow alterations, such as reservoir management, water withdrawal, wastewater discharge, stream channel engineering, evaporation of reservoir surfaces, and land use change are very well understood in terms of their effects on river flows. Engineers can predict the flow alterations due to changes in water supply operations with a high degree of accuracy. Other activities, such as the depletion of groundwater tables due to pumping and the subsequent effects on streamflows, are less understood. Table 5-4 shows the largest water supply system contributors to alteration and an indication of the understanding of the nature and extent of their effects. Because these activities can change the quantity, quality, and timing of flows, they can have significant impacts to other beneficial uses in their watershed.

Flow Alteration Activity	Average Flow	Low Flow	High Flow
Water Supply Dams	_	+	_
Surface Water Withdrawal	_	_	_
Groundwater Withdrawal	_?	_?	?
Point Sources	+	+	+
Flood Control Dams	*	?	_
Impervious Area	+	_	+

"+" an increase in the specified flow component is well captured by current modeling techniques.
"-" a decrease in the specified flow component is well captured by current modeling techniques.
"-?" a decrease in the flow component is NOT well captured by current modeling techniques.
"+?" an increase in the specified flow component is NOT well captured by current modeling techniques.
"?" indicates that changes vary on a case by case basis
"*" An asterisk indicates no appreciable change

Table 5-4: Water supply system activities and infrastructure that are the largest contributors to flow alteration in Virginia

Flow Altering Effects from Groundwater Pumping

While it is understood that some of the water that is pumped out of shallow wells "intercepts" flows bound for the stream channel, outside of the Coastal Plain the groundwater monitoring networks are too small to construct adequate predictive models over large geographic areas to say with any certainty what the likely impacts of continued and expanded pumping will be over the next 30-50 years. It can be inferred that flow alterations due to groundwater pumping effects are most likely to be noticed during low flows, making flow alterations a critical piece of information to have as pressure on the water resources grow. Also, it becomes clear that climate is not a static background variable, but one that may change substantially in a single lifetime. Therefore, as groundwater pumping within and outside of the Coastal Plain increases, monitoring networks need to expand and increase the availability of subsurface flow models to avoid being surprised by unforeseen changes to in-stream flows and groundwater system failures. In the course of the cumulative impact analysis conducted for this SWRP, areas outside of the Coastal Plain that are subject to the greatest current and future groundwater pumping will be determined, and simulations using next generation groundwater models inside of the Coastal Plain aquifers will be performed.

While great uncertainties do in fact exist, the first step in any analysis process is to collect available data for review. By examining the spatial trends in current and future groundwater pumping rates throughout the Commonwealth, an assessment of the probability that noticeable base flow impacts in a given area based on the magnitude of projected withdrawal over a given area can be developed.

Beneficial Uses and Flow Requirements

In order to assess the long-term viability of a given beneficial use, quantifying the ways in which streamflows affect that use is needed, termed generally as its "flow needs." For example, public drinking water supply requires a certain minimum amount of water each day to maintain human health. Therefore, during a drought event, there must be either sufficient "in-stream flow" to serve drinking needs, or sufficient "off-stream" or "in-stream" stored water (such as that in reservoirs). Another example would be certain migratory species that require high flows of cold water during the spring to trigger spawning runs. In general, a given beneficial uses' "flow needs" can be described in terms of the quantity, quality, and timing of water needed to maintain that use at some desired level of viability or productivity.

Critical Flow Conditions

One approach to defining flow needs is to identify the period in time, or general conditions, under which a given beneficial use is most vulnerable. This set of conditions of greatest vulnerability is often referred to as the "critical conditions" for that beneficial use. The flow needs of the various beneficial uses are understood to different degrees by scientists, with some needs being far more clearly understood than others. Given long experience with human water supply, it is relatively simple to quantify the minimum drinking water requirements for a known population of humans, with the critical condition obviously being drought. There is a good understanding of recreational flow needs and water quality needs. Additionally, there is a good understanding of the flow needs of a small number of aquatic species, but it is extremely difficult to determine the exact in-stream flow needs for all forms of aquatic life due to a lack of adequate data and targeted monitoring. As greater and greater levels of management are imposed on stream resources, an increase in both the understanding of the needs of each beneficial use and the impacts caused to other beneficial uses by water management decisions will be necessary.

Critical Periods for Beneficial Uses

Table 5-5 shows a list of eight general flow components corresponding to seasonal high and low flows, and five general beneficial uses or water supply infrastructure. An "X" indicates that the given beneficial use is susceptible to decreases in the corresponding seasonal flow component. The list of beneficial uses includes two different uses for human water supply, reservoir and direct withdrawal, because these two methods of providing off-stream water differ in terms of their critical condition. This is by no means an exhaustive list. However, it does describe the more common critical conditions faced by operations in the Commonwealth, given the historic pattern of seasonal climatic variations.

Season/Flow	Direct Withdrawals CWS/SSU/AG	Reservoir Storage CWS/SSU/AG	Aquatic Life	Waste Assimilation	Regulation of Algal Blooms
Winter High					
Winter Low		X			
Spring High			X		
Spring Low		X	X		
Summer High			X		X
Summer Low	X	X	X	X	
Fall High			X		X
Fall Low	X	X	X	X	

Table 5-5: Beneficial uses and their vulnerability to decreases in various seasonal flow conditions

Flow Needs and Cumulative Impacts

Evaluating System Stress during Drought Flows

The drought flow triggers established by the Commonwealth (see Table 5-1 and drought indicators in "Quantifying Hydrologic Drought") are useful because they represent flow values that have been shown to place stress upon the water supply system. The drought flow triggers established by the Commonwealth (see Table 5-1 and drought indicators in "Quantifying Hydrologic Drought") are useful because they represent flow values that have been shown to place stress upon the water supply system. They are a fairly common occurrence and, if stream withdrawals are high, they have a potential for ecological impact.

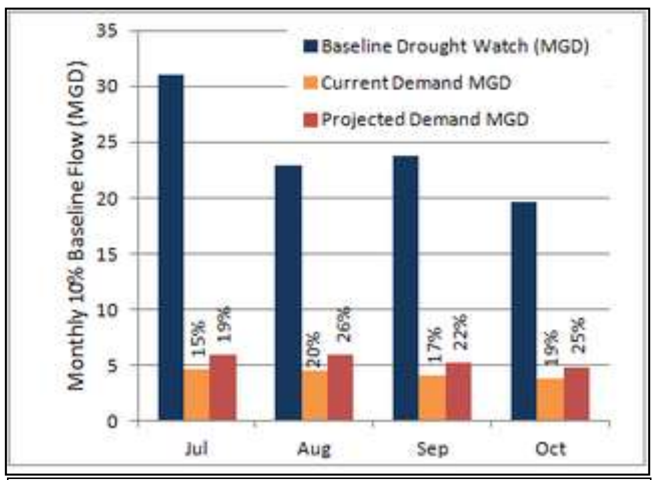

Figure 5-7: A plot of monthly 10% flows for July-October along with the current and projected mean daily surface water demands

By comparing a stream's baseline drought flow 10th percentage value to the total water demand in the stream at that time, a sense of the stress imposed on the stream and/or water supply system can be determined. For example, if a stream's demands are equal to a high percentage of its drought watch flow, this means that either downstream beneficial uses will suffer flow reductions, off-stream storage will be depleted, or demands must temporarily decrease due to drought restrictions. Figure 5-7 shows an example of this approach with current and projected surface water demand as compared to monthly baseline drought triggers in the Big Otter River for the months July-October. It can be seen that total demand in this stream is between 15-20% of the baseline drought watch value for all of these months. The projected demand is between 19-26% of the baseline water budget under drought watch conditions (the monthly 10% flow).

This metric is unique in this analysis because it aims to assess risk to multiple beneficial uses. As demands grow relative to drought flows, localities have invariably sought to augment their water supplies with stored sources of water. Aquatic biologists have long maintained that storage reservoirs may intercept storms that are critical for downstream water quality maintenance, and a recent study by the USACE at the Gathright Dam bolstered that understanding with scientific data. It was shown that harmful periphyton blooms were occurring downstream of the Gathright Dam and that these blooms could be nullified or prevented by moderately-sized storm flows being released from the Dam (for more information:
http://www.nao.usace.army.mil/Portals/31/docs/regulatory/publicnotices/2012/Dec/GathrightDamLowFlowAugmentation_EA.pdf).

Impacts to Aquatic Life

Similar to flow needs for human uses, a given stream will tend to support specific types of aquatic and riparian life because of the quantity, quality, and timing of flows that naturally occur in that stream. Flow recommendations for protection of aquatic life have varied over the years as understanding of stream biology has evolved. Two major types of data-driven efforts have historically been undertaken to quantify critical conditions for aquatic organisms:

- "Flow-Habitat" analysis, such as the In-stream Flows Incremental Methodology (IFIM), which uses stream surveys and flow measurements to predict available habitat for aquatic organisms under varying flow conditions. Available habitat can identify conditions at specific locations in the stream under critical periods, but it is very data intensive and costly.
- "Flow-Ecology" analysis uses statistical analysis of flow regimes (distribution of high, medium, low, and hydrograph shape) that are found to coincide with the life-stage needs of specific types of aquatic organisms. This analysis characterizes risk to organisms from flow alteration in streams by the percentage deviation from the reference flow regime conditions. It is less data intensive than Flow-Habitat studies, but faces the challenge of finding appropriate reference conditions.

The models developed during this process can be useful for understanding the needs of fish, aquatic insects, and riparian vegetation from both a “flow-habitat” and a “flow-ecology” perspective. Because of the diversity of aquatic and riparian species and the complex interactions amongst the different elements, the flow needs of the aquatic ecosystem are much more difficult to define than human needs. However, by evaluating changes in flow-habitat and flow-ecology metrics from the standpoint of current conditions versus future conditions, a sense of where changes are likely to occur can be determined, as well as a means for characterizing relative change between different streams. While this does not provide definitive guidance on the absolute limits of allowable change, it enables the targeting of adaptive management approaches and monitoring based on areas of greater relative change.

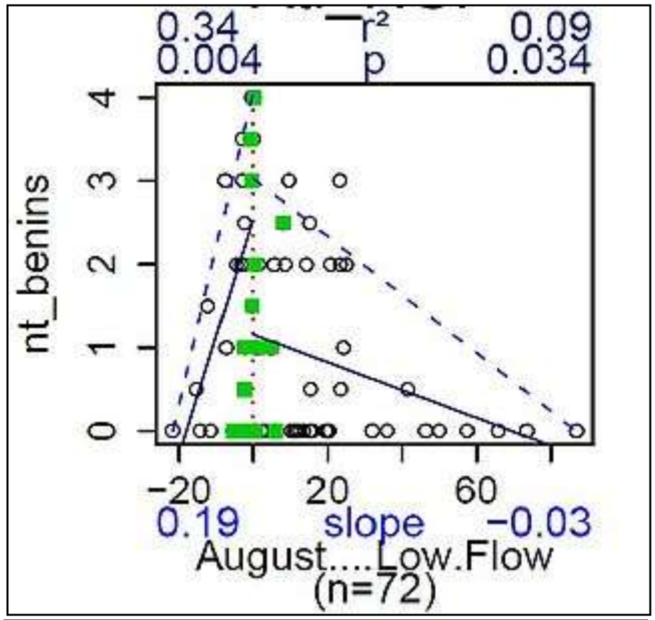

Figure 5-8: A plot of number of Taxa benthic insectivores as a function of alteration in August minimum flow in non-tidal Virginia streams (2011 USEPA sponsored Healthy Watersheds Initiative study)

Impacts to Aquatic Biology: Reductions in August Low Flow

August is considered by aquatic biologists to be a critical month for many riverine species, with a high potential for negative impacts due to flow reductions during this time. Recent research support this hypothesis, showing evidence that decreases in flows as reflected in a stream’s ALF value may result in a measurable loss of biodiversity. The ALF statistic is a good addition to the suite of metrics used in this analysis because it represents a moderate flow value more similar to the 25% Drought Watch threshold, in contrast to the Virginia five and 10% drought thresholds and the 7Q10, which tend to represent more extreme low flow conditions. Because of historical recommendations to avoid flow alterations of greater than 10% and recent studies suggesting a substantial negative impact resulting from decreases in ALF of greater than 20%, 10 and 20% changes in ALF are used to classify the severity of potential risk in maps such as that shown in Figure 5-8.

The identification of ALF as a potential indicator of aquatic system flow needs is a preliminary step in understanding the dynamic interrelationships that govern the viability of the aquatic ecosystem. By targeted monitoring of streams with larger expected impacts to ALF and by continued research into aquatic life impacts and common water supply-related flow alterations, understanding of the relationship between flows and aquatic life will increase.

Flow Alteration and Aquatic Habitat Loss

One fundamental way in which flow alterations can impact aquatic life is by changing the amount and timing of specific aquatic habitats. Different aquatic species will require different types of habitat, and the availability of this habitat is largely governed by the water flows in the system at a given time. During non-drought conditions, variations in water flows tend to reduce and/or increase different types of habitat at any given time, resulting in a very complicated relationship. Some organisms gain habitat at the expense of other organisms as the streamflows vary naturally or as a result of water supply system-induced alterations. During drought flows, especially extreme drought, virtually all types of aquatic habitat are greatly reduced, resulting in detrimental effects to most organisms. Biologists can quantify the variation in habitat by performing detailed surveys of a segment of a stream, then constructing a mathematical relationship that predicts the amount of each different type of habitat available at a given range of streamflows. The IFIM studies described earlier are very powerful tools for showing potential impacts of water supply decisions, especially under low flows when habitat loss can become critical for a majority of aquatic organisms in a given stream. These studies, while very valuable, take a considerable amount of time and effort to construct; therefore, only a handful of stream sections in the Commonwealth have had these mapping projects performed. In recent years, extensive habitat mapping has been performed in select streams, which resulted in the ability to estimate the amount of habitat that is lost or gained as a result of a specific flow alteration. Table 5-6 shows a list of streams in Virginia that have had extensive habitat mapping performed.

Stream Name	Major Basin	Year Performed
Appomattox River	James River	2011
Lower James River near Richmond	James River	1991
North Anna River	Pamunkey River	2009
North Fork Shenandoah River	Potomac River	2004
Potomac River Between Great Fall and Little Falls Dam	Potomac River	1981, 2002
Roanoke River	Roanoke River	2004
South Fork Shenandoah River	Potomac River	2012

Table 5-6: Virginia streams with completed flow-habitat modeling studies as of February 2014

These habitat maps are constructed for multiple species or groups of organisms, allowing for a very complex picture of flow-habitat relationships with a given flow alteration having varying impacts on the species or groups evaluated. Sometimes, a flow alteration that decreased habitat for one species would increase habitat for another (see Figure 5-9).

This water supply modeling and analysis effort incorporated an assessment of habitat gains/losses due to future water demands in areas where habitat modeling studies were available, but these studies are few and only a small portion of Virginia streams benefits directly from these studies. The information provided by these studies also paints a complex picture of competing habitat gains/losses between species at different flow levels and flow-alteration levels. Despite the sparseness of habitat mapping projects in Virginia, biologists with DGIF began to see certain predictable patterns emerge in flow: habitat relationships. As a result, between 2005 and 2010, DGIF biologists began to recommend that flow alterations be limited to 10% of flow during times of low flow. This recommendation was based on a study of existing flow-habitat relationships that showed that at lower flows, a 10% flow loss resulted in less than or equal to 10% habitat loss.

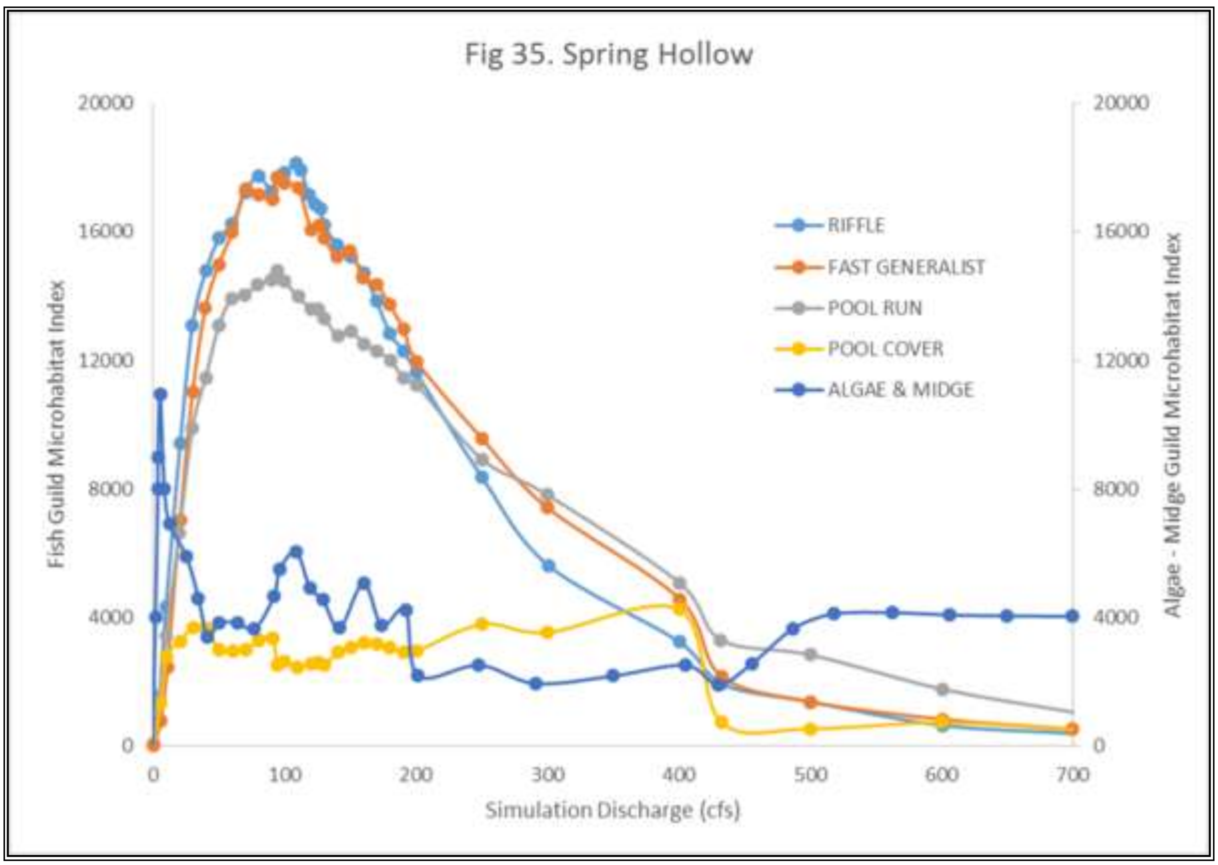

Figure 5-9: Flow-habitat relationship in the North Fork Shenandoah at the Spring Hollow sampling site from the 2004 study entitled “Stream Habitat Modeling to Support Water Management Decisions for the North Fork Shenandoah River, Virginia”

Impacts to Water Quality: Reduction in Assimilative Capacity

The “assimilative capacity” of a water body is defined as “the amount of contaminant load that can be discharged to a specific water body without exceeding water quality standards or criteria. Assimilative capacity is used to define the ability of a water body to naturally absorb and use a discharged substance without impairing water quality or harming aquatic life.” Water supply activities can impact the assimilative capacity in streams in two main ways:

- When streamflows decrease as a result of withdrawal, the waste assimilative capacity of a stream is reduced.
- Point source discharges can augment flows in streams under dry conditions. Depending upon the level of various pollutants in the point source discharge, the resulting flow can either reduce or increase the waste assimilative capacity of the receiving stream.

The waste assimilative capacity of a receiving stream may be estimated in a variety of ways, depending on the type of stream, any flow altering features (such as dams), and based on the specific pollutant of interest. Many of these estimation techniques use what is called a "design flow.” The design flow is typically a low drought flow that is considered to represent some worst case condition in the stream. Allowable pollutant loadings are then calculated based on the stream’s capacity to assimilate waste during this worst-case flow. Table 5-7 shows the full list of design flow statistics used by the VPDES program for point source regulation.

Flow Metric	Seasonal Restriction	Use
7Q10	Annual and wet season* only	DO modeling, chronic Waste Load Allocations other than Ammonia-N
1Q10	Annual and wet season* only	Acute Waste Load Allocations
30Q10	Annual and wet season* only	Chronic Ammonia-N Waste Load Allocations
30Q5		Human Health, non-carcinogenic Waste Load Allocations
Harmonic Mean		Human Health, carcinogenic Waste Load Allocations
* Wet season is defined as the months with a long term average monthly flow is greater than the long term annual average flow.		

Table 5-7: Design flows for Point Source Discharge Regulation in Virginia[62]

For this analysis, the 7Q10 was chosen as the best indicator for describing potential impacts to waste assimilation from water supply activities. The 7Q10 is defined by the USEPA as "the critical receiving streamflow used to calculate chronic aquatic life standards. It is the low flow which, on a statistical basis, would occur for a seven consecutive day period once every 10 years." In recent years, water supply needs have grown to such an extent as to lower 7Q10 values in a number of Virginia streams. Future water supply needs will result in further decreases to the 7Q10 unless withdrawal limits are constructed in such a way as to avoid these decreases. In order to achieve this goal, withdrawals would have to be reduced at time of low flow, which would require either significant reductions in demand due to conservation, or reliance on sources of water stored in reservoirs.

Modeling Changes to 7Q10

Under currently accepted practice, the 7Q10 of a given stream is calculated by analyzing the historical flow record of that stream. While there are no explicit rules for including or excluding portions of a stream's historical record from 7Q10 calculation, it is generally understood that a stream's calculated 7Q10 can be subject to significant errors if there is a large variation in the amount of flow alteration occurring during the historical record. In other words, if a stream has recently seen an increase or decrease in low flows due to withdrawals, discharges, or a change in reservoir management, then data prior to the onset of these new alterations should no longer be used in estimating the 7Q10. In cases such as this, rainfall-runoff models and the baseline flow budget that they produce can be of use to help

[62] http://www.deq.virginia.gov/Portals/0/DEQ/Water/PollutionDischargeElimination/VPDESPermitManual.pdf

distinguish the effects of flow alteration on the historical record. These models can then be run using the baseline flow budget subjected to current known flow altering effects to produce a more defensible data set for calculation of 7Q10 and other flow statistics. This approach is not without limitation since model error and model time span can introduce uncertainties into the resulting calculation. Nevertheless, as withdrawals and other flow altering factors distort the baseline flow budget to a greater extent, they can become more important than the model's own intrinsic error. Furthermore, despite the ability of model error to influence the magnitude of predicted 7Q10 changes, the models used in this study should accurately represent the direction of those changes and suffice as an indicator of the location of areas at high-risk of water-supply induced impacts to water quality.

Changes in Critical Flows Impacting Beneficial Uses

Aquatic Biology Impacts: Changes to August Low Flow

August flows are considered by biologists to represent a critical condition for many fish species, with various studies indicating declines in aquatic ecosystem health due to significant alterations in August flows. The ALF flow metric is ideal for characterizing changes in August base flows as a result of consumptive water supply demands and reservoir management rules. Projected 2040 demands are expected to affect ALF flows most significantly in the northern and eastern portions of the Commonwealth, with some small decreases in select streams in the western and southern portions of the state. For screening purposes, reaches with ALF decreases of at least 10% are considered to be at risk and need follow-up planning and monitoring. Figure 5-2 shows the median change in predicted ALF in modeled reaches for the 48 HUC's in Virginia, and Figure 5-3 shows the predicted decrease in the 10% most highly impacted reaches in each HUC. Basins with significant decreases in ALF are as follows:

- Potomac-Shenandoah River Basin
    - Shenandoah River North and South Fork: Reaches in this Basin are projected to have a median change in ALF of less than 5%, but with individual streams projected to experience reductions of 10-20%.
    - Middle and Lower Potomac River streams are predicted to have a median change of less than 1 %; however, reductions of 10-20% are predicted in select streams. The main stem of the Potomac River above the fall line has predicted decreases of less than or equal to 5%.
- James River Basin represents a diverse set of conditions with small increases, or no change in ALF predicted in much of the upper reaches of the watershed above Lynchburg, with median decreases of less than 5% in the non-tidal reaches in the middle and lower portion of the watershed. Approximately 10% of individual stream reaches are expected to see decreases of between 10-20%.

- York River Basin: Increased withdrawals from unregulated impoundments on the Ni River are expected to decrease downstream ALF by 10-20% in the reaches of the Mattaponi unless specific reservoir management rules and releases are in place to preserve in-stream flows.

Major basins that are predicted to have reaches with increasing ALF as a result of declining surface water demands or as a result of low flow augmentation from reservoirs are:

- James River Basin: The stretch of the James River below Cartersville/Cobbs Creek project[63] to the fall line are predicted to see increased ALF in the range of 1 -10% due to the low flow augmentation activities from the Cobb's Creek project. These low-flow augmentation releases are expected to increase ALF despite an increase of approximately 30-40 MGD above the Cobbs Creek intake.
- Albemarle-Chowan River Basin: Decreases in demand in the headwaters of the Nottoway River basin are predicted to result in small increases to ALF (less than 10%).
- Tennessee-Big Sandy River Basin: Select segments in the headwaters of the Clinch River Basin are predicted to have increasing August Low Flows as a result of declining surface water demands.

[63] The Cobbs Creek Reservoir project is a new regional pumped storage reservoir in northern Cumberland County near the James River that will provide 14.8 billion gallons of raw water storage within a 1,107 acre normal pool area. The reservoir's primary water source will be obtained from an intake on the James River, which will transfer water when flows in the river are adequate. The multi-purpose reservoir will serve to provide additional water storage in the James River watershed for Henrico County's and its regional partners' public water supply projects, provide a recreational amenity to visitors and citizens of Cumberland County, and provide flow augmentation releases to the James River during low flows and droughts. Flow augmentation releases from the Cobb Creek Reservoir to the James River are designed to supplement flows during low flows or droughts in the 45 mile stream reach between the release point to Henrico County's existing intake located downstream near Richmond. These releases are to offset the effect of new or increased withdrawals from the James River by Henrico County and its regional Partners to mitigate the withdrawal's impact on aquatic habitat and other existing beneficial uses. Releases will occur from June through November, which are the months with the statistically lowest flows in the James River. When flows at the USGS James River at Cartersville, VA stream gage (No. 02035000) are between the 5th and 30th percentile monthly flow levels, release will occur to offset new or existing withdrawals. When flows are below the 5th percentile monthly flow levels, releases will be provided to try to increase stream flows at the aforementioned UGSG gage to the 5th percentile, with a maximum release of 100 MGD.

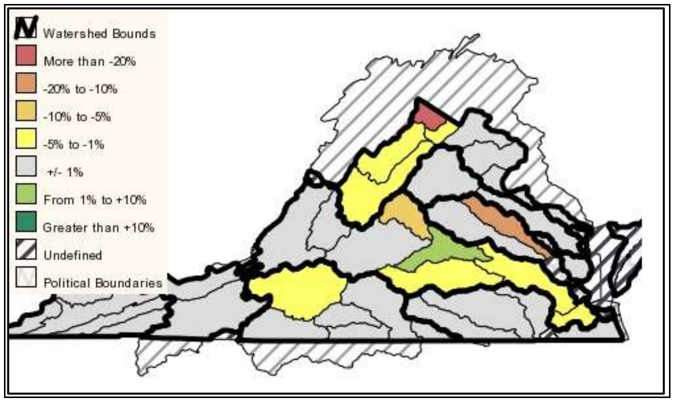

Figure 5-10 Median change in August Low Flow by HUC

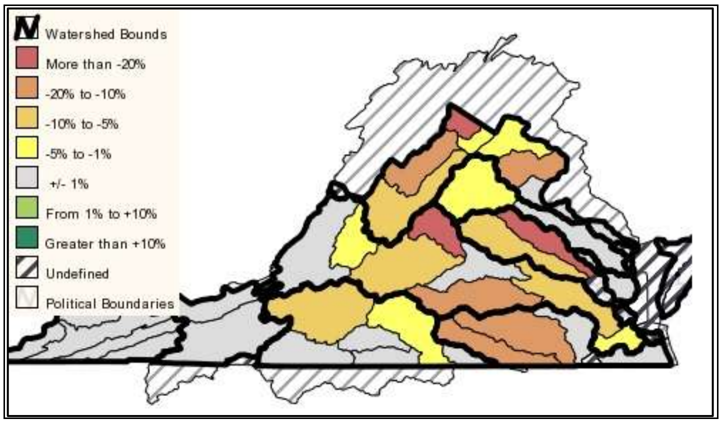

Figure 5-11 Projected changes in ALF for the most highly impacted 10% of watersheds in each HUC

Water Quality Impacts: Projected Changes to 7Q10

As described earlier, 7Q10 is one of a host of flow statistics that is used by regulatory agencies to estimate the waste assimilative capacity of rivers, and is used to set allowable effluent limits for point source discharges. Decreases to 7Q10 flows may result in decreased assimilative capacity, which may result in reduced effluent limits for regulated point sources to prevent water quality degradation. Margins of safety vary from permit to permit, so a 5% decrease in 7Q10 was set as a conservative screening threshold for recommending follow-up planning and monitoring. Figure 5-12 shows the median change in predicted 7Q10 in modeled reaches for the 48 HUC8's in Virginia, and Figure 5-13 shows the predicted decrease in the 10% most highly impacted reaches in each HUC. Basins with reaches that are predicted to see significant decreases in 7Q10 are as follows:

- James River Basin: Flows between Lynchburg and the confluence with the Rivanna River are predicted to see reductions between 5-10% in 7Q10, until flow augmentations from Cobbs Creek ameliorate these decreases. Flows in some headwater reaches of the Appomattox River are predicted to have 7Q10 flows that decrease by 5-20%, reducing 7Q10 inflows to Lake Chesdin. Due to release rules that are oriented towards preserving low flows, flow below Lake Chesdin is expected to decrease less than 5%, with the river soon becoming tidally influenced and no longer limited by 7Q10.

- Potomac-Shenandoah River Basin
  - Potomac – Median change of less than 1%; however, main stem Middle Potomac River through this segment from Point of Rocks to the fall line is expected to see a decrease of approximately 5%.
  - Shenandoah River Basin - Reductions of 10-20% in 7Q10 are possible in North and South Fork Shenandoah. Point sources augmentation may reduce much of this, especially since groundwater withdrawals are expected to supply approximately 50% of new withdrawals. In the short term, this groundwater pumping may result in flow augmentation as point source return flows, but in the long term, groundwater pumping may lead to reduced base flows in streams.
- Rappahannock River Basin – Mild reductions in 7Q10, with a mix of increases below the Greene County Reservoir and small decreases in Upper Rappahannock and near Fredericksburg.
- Roanoke River Basin - Select reaches in the Upper Roanoke HUC are predicted to see decreases of as much as 10%; however, overall the Roanoke drainage median decrease in 7Q10 is less than 1%.
- York River Basin – Due to increased energy production, draw downs in Lake Anna are expected to increase. Operational rules in Lake Anna require release to be tied in part to reservoir storage amounts and are predicted to decrease 7Q10 flows. Increased demands below Lake Anna are also expected to contribute further to this decrease. Increased withdrawals from unregulated impoundments on the Ni River are expected to decrease downstream flows unless specific reservoir management rules and releases are in place to preserve downstream assimilative capacity.

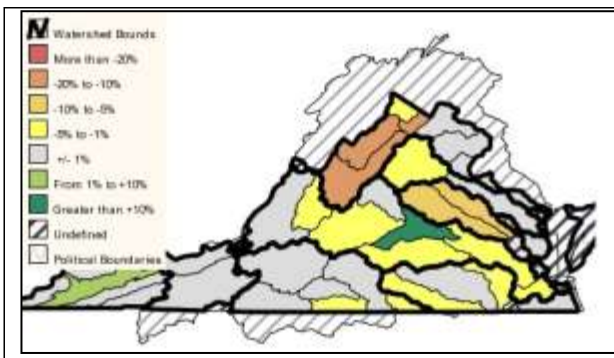

Figure 5-12: Median projected changes in 7Q10 by HUC

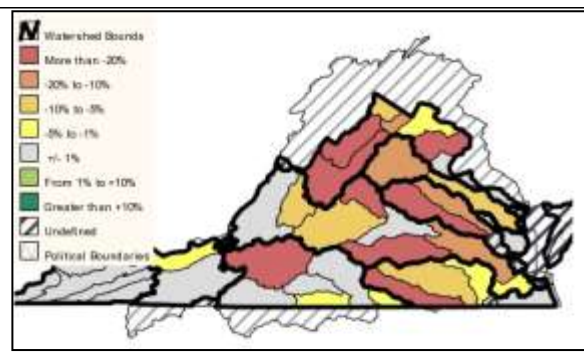

Figure 5-13: Projected changes in 7Q10 for the most highly impacted 10% of watersheds in each HUC

Major basins that are predicted to have reaches with increasing 7Q10 as a result of declining surface water demands or as a result of low flow augmentation from reservoirs are:

- James River Basin- The stretch of the James River below Cartersville to the fall line are predicted to see increased 7Q10 of greater than 10% due to the low flow augmentation activities from the Cobbs Creek project.
    - Lower James near Virginia Beach – probably statistical anomaly.
- Tennessee/Big Sandy River Basin- Select segments in the headwaters of the Clinch River basin are predicted to have increasing ALF as a result of declining surface water demands.

Water Availability: Changes in September Drought of Record Flow

The ability for water supply systems to meet off-stream demand is often referred to a "safe yield," which is by definition the highest average annual volumetric rate of water that can be withdrawn by a surface water withdrawal during the worst DoR in Virginia since 1930. . Because cumulative consumptive withdrawals of surface water reduce streamflows, a future occurrence of the same meteorological conditions that led to DoR flows would produce even lower flows if consumptive demands were higher than those present during the DoR. A 5% decrease in September mean flow during the DoR was set as a conservative screening threshold for recommending follow-up planning and monitoring. Important variables to quantify to determine actual risk of reduced DoR flows will be consumptive fractions of new demands and the potential effectiveness of conservation ordinances and practices. Figure 5-14 shows the median predicted decrease in September DoR flow, and Figure 5-15 shows the decrease predicted for the 10% most highly impacted reaches by HUC. Basins with reaches that are predicted to see significant decreases in DoR flows as a result of increased consumptive withdrawals are as follows:

- James River Basin - Decrease in September DoR of between 5-10% were predicted for select reaches in the Middle James between Lynchburg and Cartersville and for areas of the Chickahominy River.
- Potomac-Shenandoah River Basin - The South Fork Shenandoah River is predicted to see median DoR flows decrease by at least 10%, with 10% of reaches in the North Fork Shenandoah, Upper Potomac, and Middle Potomac seeing decreases of 10-20%.
- Roanoke River Basin - 10% of reaches in the Upper Roanoke watershed are predicted to have DoR reductions of 10-20%; however, the median change is predicted to be less than 1%.
- York River Basin - The York is overall the most highly susceptible watershed, with median decreases of between 10-20% predicted and 10% of reaches predicted to see at least a 20 % decrease in DoR flow as a result of increased consumptive withdrawals.

Major basins that are predicted to have reaches with increasing DoR as a result of declining surface water demands, or as a result of low flow augmentation from reservoirs are:

- James River Basin - The stretch of the James River below Cartersville to the fall line are predicted to see increased DoR flows of greater than 10% due to the low flow augmentation activities from the Cobbs Creek project.

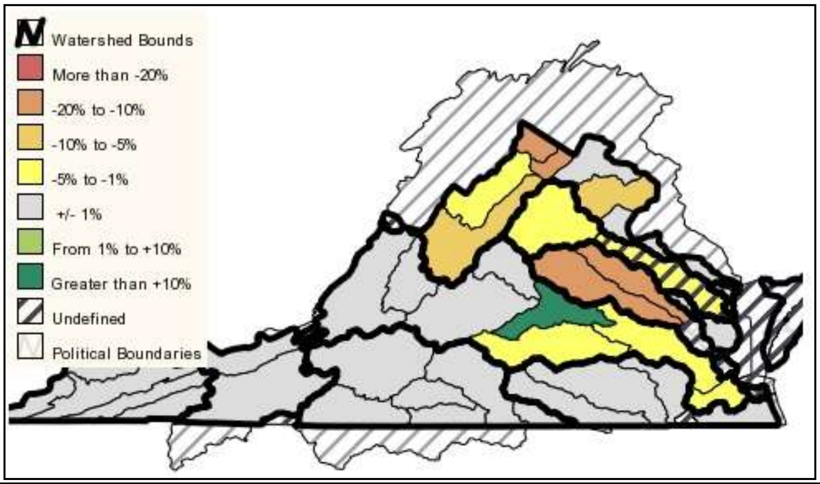

Figure 5-14: Median change in September drought of record flow by hydrologic boundaries

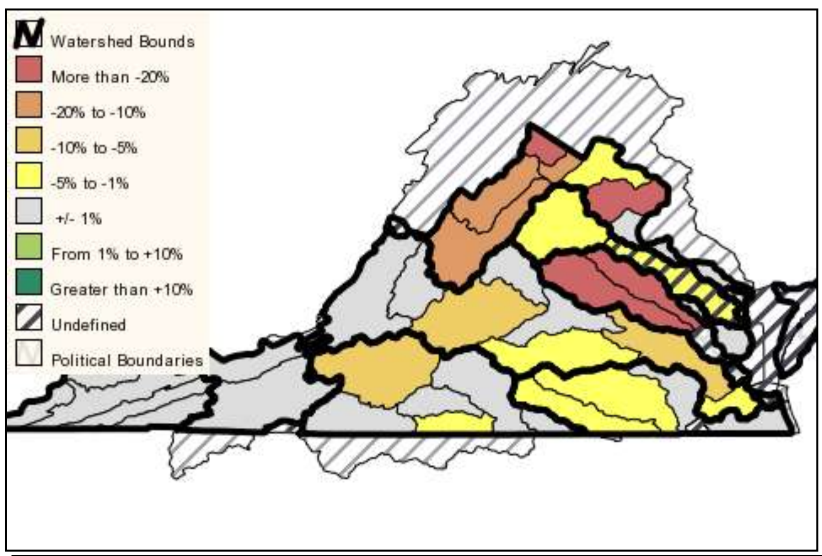

Figure 5-15: Projected changes in September drought of record flow for the most highly impacted 10% of watersheds in each HUC

System Stress: Withdrawals as Percentage of Baseline Drought Flow

By comparing a stream's baseline drought flow values to the total water demand in the stream, a sense of the stress imposed on the stream and/or water supply system can be obtained. If a stream's demands are equal to a high percentage of its baseline flow at any time, this means that either downstream beneficial uses will see flow reductions, reservoir storage will be depleted, or off-stream demands must temporarily decrease due to conservation restrictions. Reaches with cumulative projected demands greater than 25% of September drought warning flows are considered candidates for recommending follow-up planning and monitoring.

All major basins, even those with net declining withdrawals, are projected to have at least some stream reaches that are predicted to have mean withdrawals that are greater than 30% of September Drought Warning flow, indicating a moderate to high level of overall water system stress. Areas of the Potomac, York, Rappahannock, and James River Basins are projected to see median level of water system stress above the 30% level.

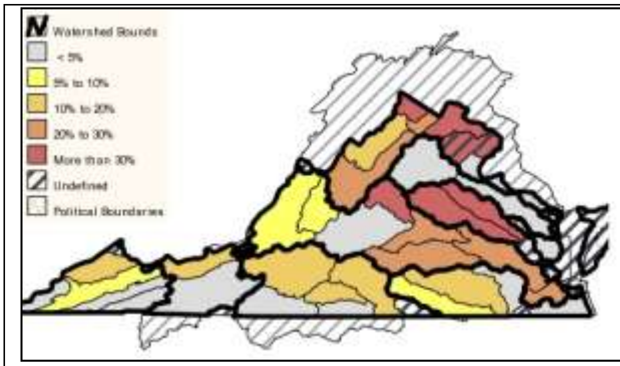

Figure 5-16: Median Cumulative withdrawals as a percentage of September Drought Warning flow in Virginia by 8-Digit NHD HUC

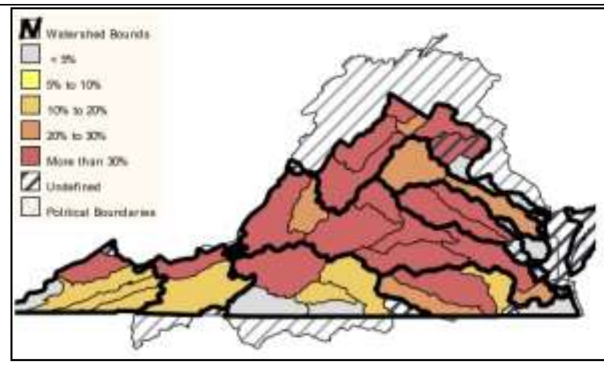

Figure 5-17: Cumulative withdrawals as a percentage of September Drought Warning flow for the most highly impacted 10% of watersheds in each HUC

Cumulative Effects of Groundwater Pumping

Groundwater is expected to provide approximately 23% of water demands by the year 2040. Approximately 75% of this groundwater demand is expected to occur outside of the Coastal Plain Groundwater Management Areas. While the area inside the Coastal Plain is capable of being modeled for cumulative groundwater impacts, understanding of the groundwater dynamics outside the Coastal Plain is hampered by a lack of monitoring wells and by the heterogeneity of the unconsolidated surficial aquifers that characterize this area. Also, the groundwater demands outside of the Coastal Plain are dominated by small residential users, so the spatial resolution of the data submitted limits understanding further to the locality scale. Despite these limitations, the data gathered during this water supply planning process gives a far more complete picture of the geographic distribution and magnitude of groundwater demands and their potential rates of change than was previously possible. Figure 5-19 shows a map of projected groundwater demands in 2040 in units of million gallons per year (MGY) per square mile, and Table 5-9 shows the statistical distribution of mean projected pumping rates in 2040 by locality. Given the lack of data outside of the Coastal Plain, it is difficult to provide any risk assessment based on an actual detailed physical understanding of the system. However, a comparative risk assessment which ranks individual localities according to their groundwater unit area pumping rates is within current capabilities. Areas with greater than approximately 0.3 MGY per square mile are considered to be in the upper 25 %

in terms of risk for negative impacts due to groundwater pumping. Outside of the Coastal Plain, 17 localities are projected to exceed this threshold in 2040.

When looking at projected demands for groundwater within the GWMA of Virginia, DEQ is able to use actual withdrawal data provided through VWWR and reporting required by Groundwater Withdrawal Permits, with the projected values based on the NASS Census data. Since private wells are not regulated unless withdrawals are above the 300,000 gallons per month value, the residential demand served by private wells was estimated.

The percentage of total 2040 water use derived from groundwater sources is estimated at 25%; therefore, the groundwater use is estimated to increase from 380 MGD in 2010 to 445 MGD in 2040.

Within the Coastal Plain, the affects of the projected demand for groundwater withdrawals can be modeled using VAHydro–GW. This is the same modeling tool used to complete the Technical Evaluations used for the Groundwater Withdrawal Permitting. The current model uses the 2006 updated framework (McFarland and Bruce, 2006[64]) along with reported and permitted withdrawal up through 2012.

Figure 5-18 depicts the simulation of the estimated domestic non-permitted wells in Virginia with the known permitted wells at their current estimated pumping rates, then increasing their pumping rates over the duration of the simulation to the projected 30-year pumping value for each well. The VAHydro-GW simulation was executed for a full 50 years, even though the water supply planning evaluations are projected out for 30 years. Table 5-8 outlines the pumping values involved in the planning simulation. The 2013 Total Permitted Simulation pumping values are also included in the following table for reference.

Permitted Wells					
	VAHydro-GW Simulation Year				
	2013-2022	**2023-2032**	**2033-2042**	**2043-2052**	**2053-2062**
30 Year Planning Scenario (MGD)	76	92.6	109.1	125.7	142.3
2013 Total Permitted Simulation (MGD)	120.2	120.2	120.2	120.2	120.2

[64] http://pubs.usgs.gov/pp/2006/1731/pp1731_download.htm

Domestic Wells					
	VAHydro-GW Simulation Year				
	2013-2022	**2023-2032**	**2033-2042**	**2043-2052**	**2053-2062**
30 Year Planning Scenario (MGD)	33.6	35.7	37.7	39.8	41.8
2013 Total Permitted Simulation (MGD)	25.2	25.2	25.2	25.2	25.2

Table 5-8 Pumping Values involved in planning simulation

The following figures show that if withdrawals were to occur at the projected water supply planning rates, the critical cells would increase over the projected period. The white squares show the projected critical cells from the current total permitted withdrawals. The orange squares illustrate the increase in those critical cells if the projected values were reached. This figure of the Potomac aquifer is an illustration of how critical cells would increase by over 500 cells, indicating that those areas in orange would be overdrawn in a non-sustainable way, resulting in reduced head and potentially irreversible damage to the aquifer system that may result in increases in saltwater intrusion and land subsidence.

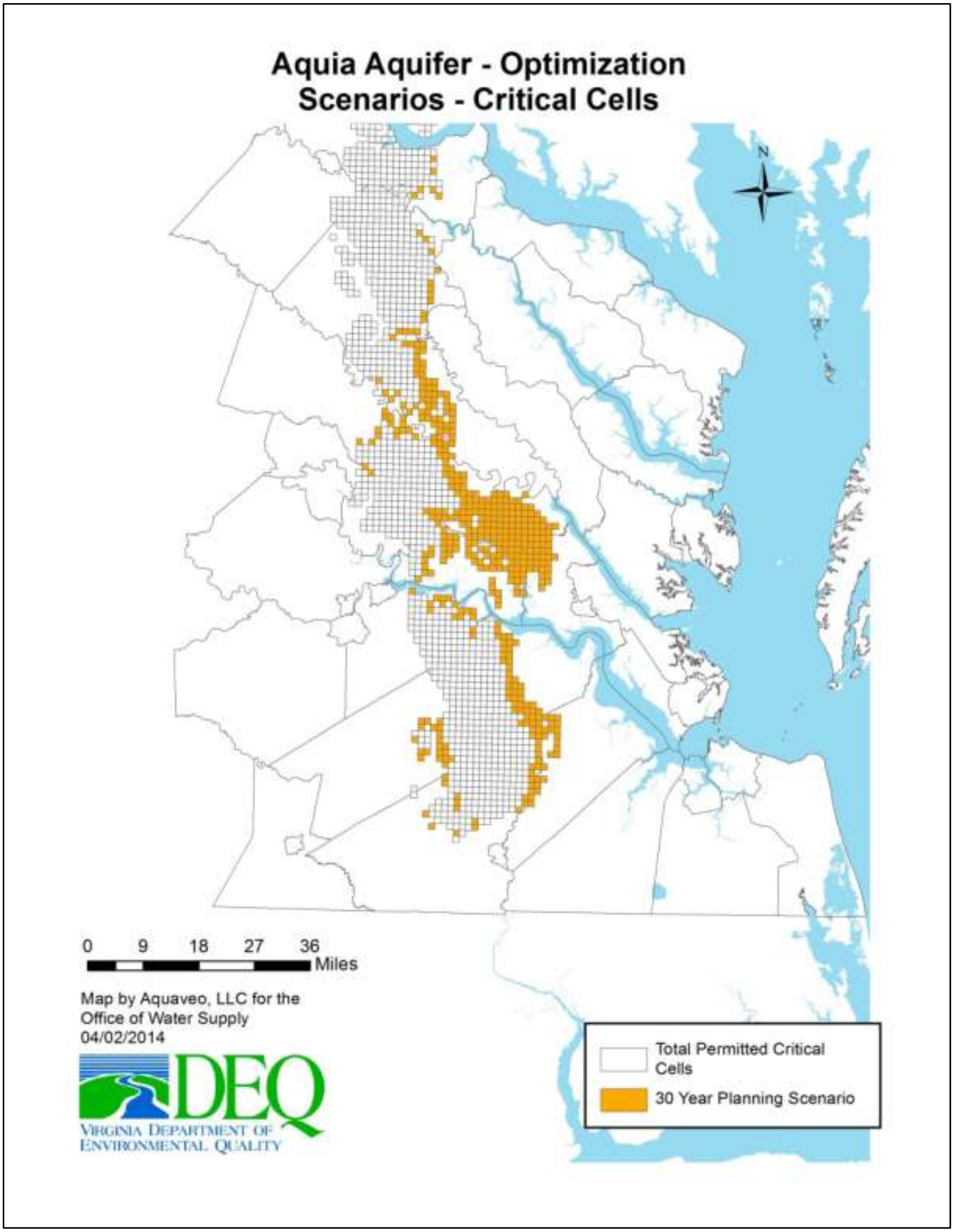

Figure 5-18 Aquia Aquifer

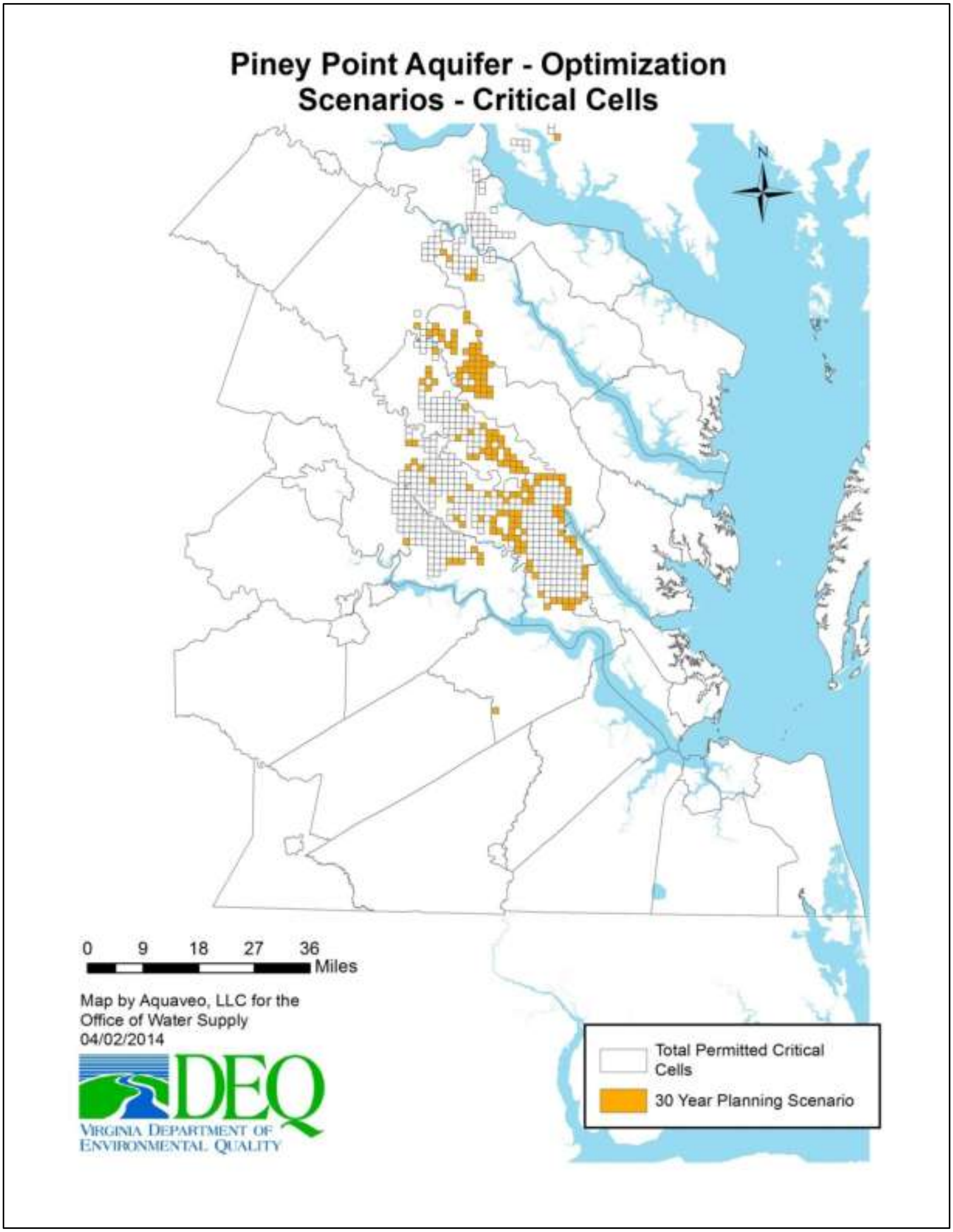

Figure 5-19 Piney Point Aquifer

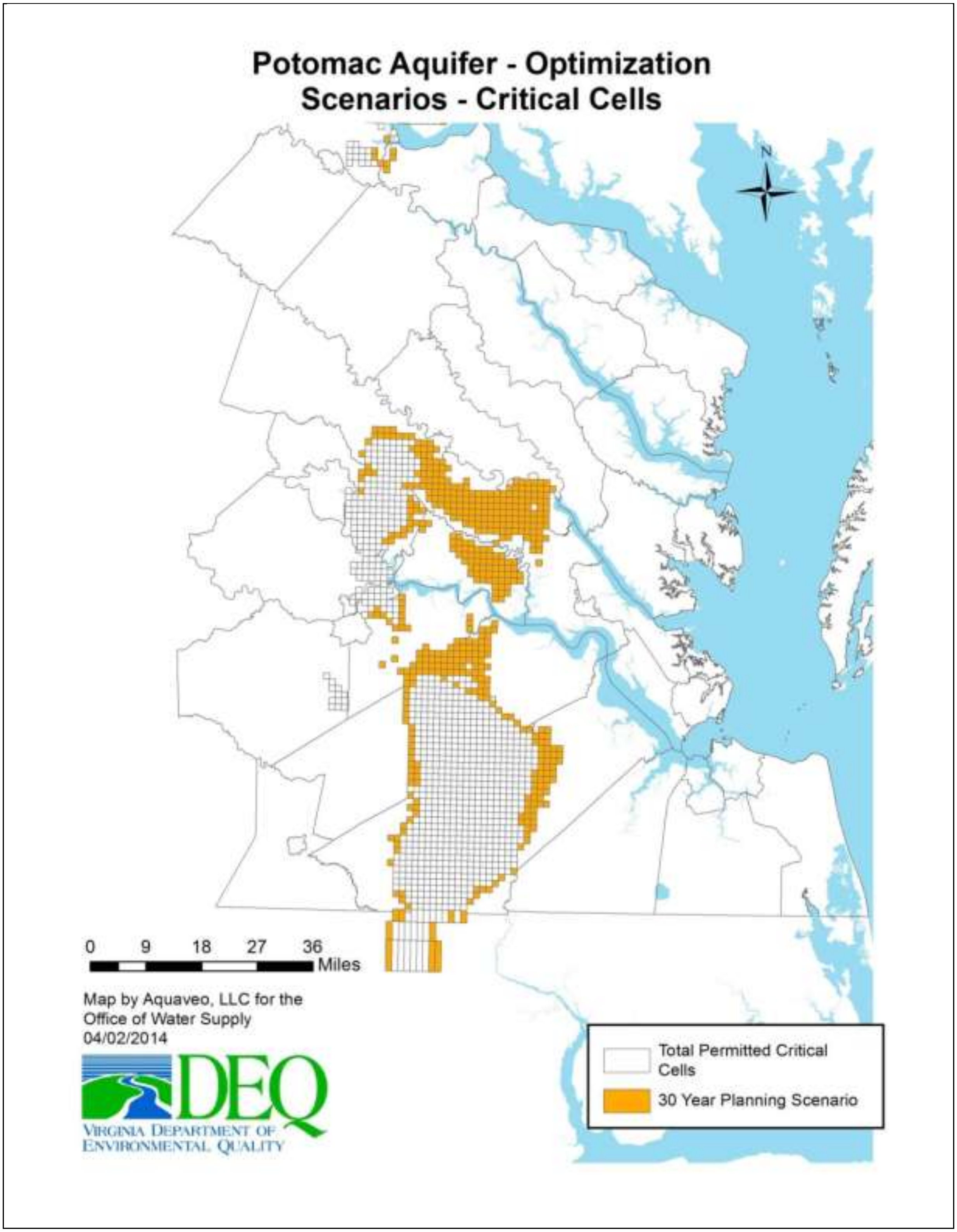

Figure 5-20 Potomac Aquifer

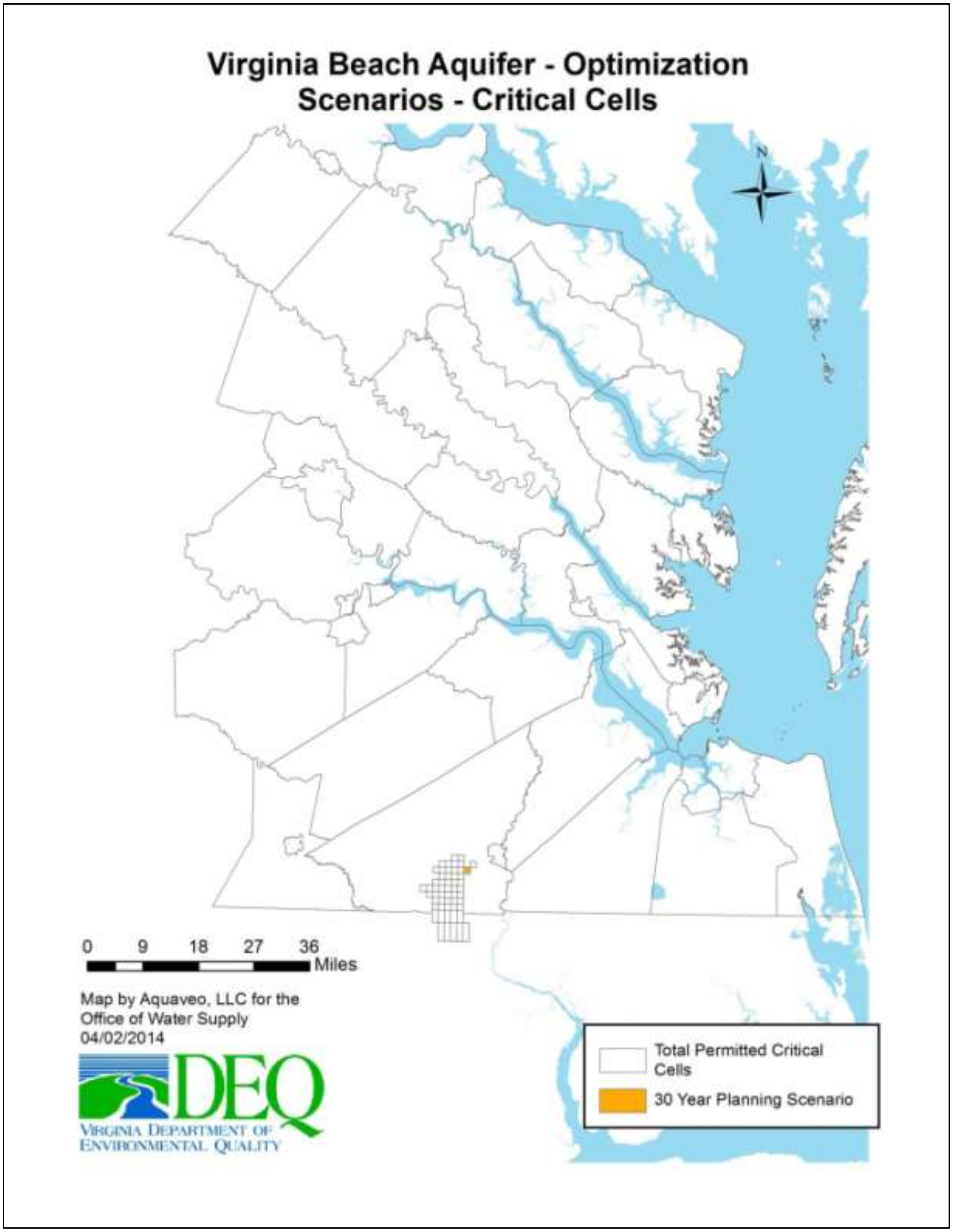

Figure 5-21 Virginia Beach Aquifer

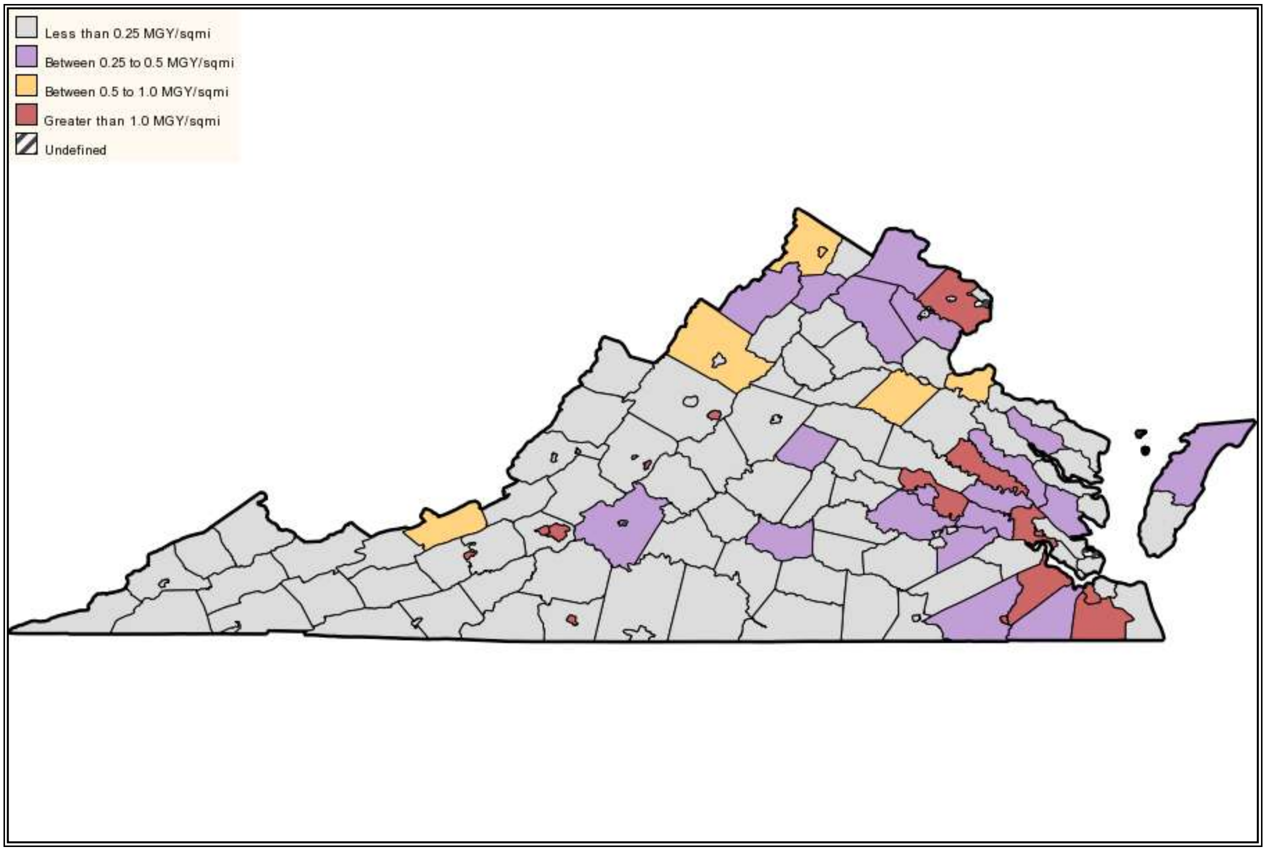

Figure 5-22: Projected groundwater demand in 2040 givein in MGY/square mile. This data is presented by Federal Information Processing Standards (FIPS) locality because the resolution of Water Supply Plan residential groundwater data is limited to the locality scale

Lowest 25 Percent Rate of Pumping (MGY / Square Mile)	Median Rate of Pumping (MGY / Square Mile)	Highest 25 Percent Rate of Pumping (MGY / Square Mile)
0.0445	0.1255	0.298

Table 5-9: 25th, 50th, and 75th Quantile values for total estimated 2040 groundwater pumping rates reported by localities. Rates were calculated in MGY/square miles, which is total water from groundwater in MGY in a locality divided by the locality's area in square miles.

Cumulative Impacts Analysis: Conclusions

The data and information submitted during this water supply planning process predicted a net increase of approximately 32% in mean daily water supply demand. Within this average overall increase, rates of change varied geographically, with a mixture of large, moderate, and small increases, as well as a small number of areas with a decreasing or static trend in water supply demand. Table 5-10 lists the percentage of streams, by major basin, that are predicted to suffer significant reductions in flow as a result of 2040 demand increases. A brief summary of impacts in the 327 non-tidal river reaches modeled Commonwealth-wide is as follows:

- 7 % are predicted to have a significant decrease in August Low Flows.
- 16% are predicted to see a significant decrease in September mean flow under historic drought of record conditions.
- 24% of reaches are predicted to see a potentially significant decrease in 7Q10 as a result of water supply activities.
- 26% are expected to represent a significant level of overall system stress as evaluated by withdrawals as a percent of September drought warning flows.

These summary statistics portray a future that may be marked by widespread areas of little to moderate impacts under normal conditions, punctuated by isolated areas with significant chronic impacts, and moving towards more widespread impacts under the driest conditions. Under moderately dry, but non-drought conditions such as those represented by the ALF, projected critical areas represent a small (7%), but significant portion of Commonwealth stream reaches. While these ALF impacts may in fact represent a serious concern for aquatic system health, the results of this modeling and analysis also suggest that this may not be an inevitable consequence. A number of areas were shown to be able to meet large demand increases while also preventing changes to ALF through carefully planned withdrawal rules and use of stored water. Similarly, management rules and use of storage was predicted to mitigate potential reductions to 7Q10 and drought warning flows. During the drought of record simulation, however, the challenge to the full range of beneficial uses will require greater attention in the follow-up to this plan. Nearly 97% of the projected surface water demands in Virginia's streams are projected to come from approximately 25% of the stream reaches simulated. With 16% of streams predicted to see greater than 5% reduction in drought of record flows, this indicates a high probability that new management and/or infrastructure will be required to maintain safe yields at current levels. While systems that have built or are planning to build new storage will likely have adequate reserves to meet the predicted reduced drought inflows, systems without storage or with demands that are nearing existing safe yield will face stiff challenges as the cumulative demands on streams increases.

Moving forward it should be noted that increased storage is not the only solution that can be implemented, nor is it a solution without its potential downsides. As understanding of the impacts of flow alteration from large impoundment activities improves, there may be a need to devote resources and management efforts to balancing the need for stored water with flushing flows to maintain downstream algal populations at desirable levels. Given the relatively modest flow impacts predicted in many areas, attention should be paid to the role of conservation and drought restrictions to reduce demands during critical periods. Similarly, understanding monthly demand trends and exploring ways to shift demands away from the driest months and towards wetter months may be one of the most powerful methods of securing stable safe yields in the future.

This plan provided an opportunity to see the likely challenges that will be faced by the many beneficial uses that depend on flow in Virginia's streams. The information provided enables the identification of the probable location and types of impacts and the various regulatory, infrastructure, and ecological challenges that these impacts might present. In addition to these areas of likely impact, the information in this plan can be used to target areas whose demands reach or exceed the plan projections. Areas whose growth exceeds predictions will require better understanding of aquatic resources, a more intense scrutiny to the accuracy of data, and a more thorough knowledge of water supply operations in that area.

Basin	**% Increase Water Demand 2010-2040**	**2040 % Basin Decrease ALF >10%**	**2040 % Basin Decrease 7Q10 > 5%**	**2040% Basin Withdrawal >25% of September Drought Warning**	**2040 % Basin Decrease September DoR > 5%**
Chesapeake Bay-Small Coastal	+14%	NA	NA	NA	NA
Chowan-Albemarle River Basin	+21%	12%	19%	19%	8%
James River Basin	+37%	10%	29%	41%	10%
New River Basin	+5%	0%	0%	3%	0%
Potomac-Shenandoah River Basin	+33%	12%	39%	31%	32%
Rappahannock River Basin	+83%	0%	29%	14%	7%
Roanoke River Basin	+24%	2%	11%	13%	7%
Tennessee-Big Sandy River Basin	-5%	0%	0%	12%	4%
York River Basin	+50%	18%	53%	65%	59%
Commonwealth of Virginia	+32%	7%	24%	26%	16%

Table 5-9: Modeled changes to key indicators for watersheds in Virginia based on projected demand changes from 2010-2040