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RESEARCH ARTICLE

Evaluation of surface water supply impacts from permit exemptions: A comparison with climate change and demand growth

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Abstract

Many states in the Eastern U.S. have limited water withdrawal regulations, posing significant risks to water supply management during periods of low flows. While these states require water withdrawal permits, exemptions for grandfathered withdrawals that allow unregulated access to surface water are common. Such permit exemptions present a challenge to water supply management, as full utilization of allowable withdrawals by permit-exempt users could pose risks to maintaining adequate water supplies for current and projected demand. This study used reported permit exemption data in Virginia to understand the extent, volume, and potential impact of permit-exempt withdrawals on 30- and 90-day low flows. The permit-exempt withdrawal values used in this study were obtained from Virginia Department of Environmental Quality. Maximum permit-exempt withdrawal volumes were significantly higher than projected future demands in permitted users. The impacts of these withdrawals on drought flows were compared with the impacts presented by climate change and demand growth. Widespread reduction in flows was observed with the "dry" future climate change scenario, while impacts were more localized in the exempt users and the demand growth scenarios. The impacts of exempt users exceeded the impact of climate change and demand growth scenarios in many regions during low-flow periods. Therefore, more comprehensive water planning, policy and research is needed to address the impact of permit exemptions.

KEYWORDS
water withdrawals, water supply, water policy, drought, planning, environmental impacts, permit exempt

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Research Impact Statement

Impacts from permit-exempt water withdrawals were more severe than dry climate change and 2040 demand growth scenarios within regions across Virginia.

1 | INTRODUCTION

As of 2015, the United States Geological Survey (USGS) reported annual water withdrawals of 1.2×10^9 m^3 per day in the United States (U.S.), with 74% of water originating from surface water withdrawals (Dieter et al., 2018). With a projected U.S. population of over 400 million by 2058 (Vespa et al., 2020), pressure on our freshwater resources, combined with climate change, will affect water availability in all sectors such as industry, agriculture, municipal and domestic use (He et al., 2017). According to the U.S. Environmental Protection Agency (EPA), water shortages will likely be experienced in at least 40 states by 2024 (U.S. Government Accountability Office, 2014). Adapting to future conditions requires a focus on the sustainable management of water resources, addressing challenges such as increased water demands, climate change impacts, and limitations of existing law. Despite relatively high precipitation resulting in generally adequate freshwater supply, humid regions within the mid-Atlantic such as Virginia (VA) have experienced droughts regularly, including 1930–1932, 1962–1971, 1985–1988, 1999–2002, and 2007–2009 (Virginia|Drought.Gov). In the US, droughts result in a loss of nearly 9 billion dollars per year, resulting in long-lasting, substantial socio-economic impacts (NOAA, 2020). Overall, in the US, droughts result in a loss of nearly $9 billion per year (NOAA, 2020), leading to substantial socio-economic impacts such as reduced agricultural yields (Reyes & Elias, 2019), increased fire risk (Smith, 2020), and declines in recreational revenue (Cutler et al., 2017).

Traditionally, water allocation in the Eastern U.S. was made using a riparian water law legal framework. Riparian law gives a riparian landowner a right to withdraw a reasonable amount of water provided it does not result in the deprivation of other riparian's reasonable use of the water. Due to inherent ambiguity about reasonable withdrawal amounts, this framework has been criticized for lack of protection for water resources (Gould, 2002). To manage this ambiguity regarding what is reasonable, many states aimed to define the reasonable use notion with permit-based water withdrawal structures to bring oversight and predictability to the process of water allocation. Like many states in the U.S., the Virginia Department of Environmental Quality (VDEQ) requires users to have a Virginia Water Protection (VWP) permit for any activity that involves filling, draining, withdrawing from or excavation of state surface waters. Surface water withdrawals are defined as removal or diversion of surface water in Virginia for consumptive or nonconsumptive use, thereby altering the instream flow or hydrologic regime of the surface water (VAC, 2016a). Through the VWP permitting program, VDEQ manages permitted water withdrawals to promote the long-term sustainability of water supply while seeking to balance competing beneficial uses such as aquatic life, recreation, and waste assimilative capacity. However, not all VA users must get a VWP permit for water withdrawals. Such unpermitted withdrawals are not bound by water withdrawal conditions normally associated with a VWP permit. First, in non-tidal waters (inland areas without tidal influx of water), VWP permits are not required for surface withdrawals below 1 million gallons (3785 m^3) in a single month for agricultural use and below 10,000 gallons (37.85 m^3) per day for non-agricultural users. In tidal waters (areas influenced by tidal fluctuations), the permits are not required for agricultural withdrawals below 60 million gallons (227,124 m^3) in a single month and below 2 million gallons (7570 m^3) per day for other uses (VAC, 2016b). Additionally, grandfathered (Before July 1989) water withdrawals that were in existence before July 1, 1989, are excluded from the requirement to obtain a permit unless a new § 401 certification is required to increase a withdrawal (VAC, 2021). Additional exemptions for surface water withdrawal permits are listed in the VAC, 2016b.

Approximately 82% and 77% of the total volume of surface water withdrawn in VA in 2013 and 2017, respectively, was excluded from permitting (VDEQ, 2022). Unpermitted withdrawals are required to implement conservation and water use restrictions, such as during a drought emergency in accordance with local drought water conservation and contingency plans or the mandatory restrictions listed in the statewide Drought Assessment and Response Plan (Virginia Drought Assessment and Response Plan, 2003). However, these conservation actions only have the force of law when part of an Executive Order or within a surface water management area declared as such pursuant to Virginia Administrative Code (VAC) § 62.1–254, 1992. When located downstream of unpermitted users, permitted users would likely be dependent on reasonable water withdrawal by unpermitted users during short-term low flows, particularly where a drought emergency is not called. This situation creates considerable uncertainty regarding the volume of water that exempt users might withdraw under different circumstances, resulting in challenges for determining water supply availability under additional planning and operational conditions.

Similar permit exemptions also exist in other states across the U.S., where certain users are exempt from having a permit. For example, Georgia has no minimum flow requirements for water users withdrawing water before 1988 (Board of Natural Resources, State of Georgia, 2001). Similarly, South Carolina's 2011 Surface Water Withdrawal Act considered the amount a particular entity could withdraw as of January 1, 2011, to be exempt from permitting. In Pennsylvania, surface water withdrawals of 100,000 gallons (378 m^3) per day or more initiated before November 11, 1995, and consumptive water use of 20,000 gallons (75 m^3) per day from any source in place before January 23, 1971, are exempt. Any surface water withdrawals in place before April 1, 1985, are exempt from acquiring a water permit in Mississippi. Similar

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exemptions are found in other states and are listed in Table S1. Water withdrawals below the permitting threshold or reporting threshold are typically unaccounted water withdrawals in management programs. The unaccounted withdrawals result in high cumulative impacts in highly populated areas and small watersheds (Palmer & Moltz, 2013). In largely rural settings, these unpermitted uses represent a substantial proportion of total withdrawals, for example, 49% in a Pennsylvania watershed study (Moltz & Palmer, 2012).

The potential impacts of these statutory and regulatory exemptions have the capacity to compound the effects of other long-term water supply stressors, such as climate change and increasing demand. Growing water scarcity issues are directly associated with increased demand for water driven by population and economic growth (Boretti & Rosa, 2019). The United Nations estimates that at least 57% of the global population will live in areas experiencing water scarcity for at least 1 month each year by 2050 (UNESCO World Water Assessment Programme, 2018). VA is no exception, where the population is expected to increase from 8.6 million in 2020 to 9.8 million in 2040 (Lombard, 2020). Despite decreases in per capita water use (Larsen, 2015; USGS, 2018), multiple locations in VA are expected to experience growth in water demands (VDEQ, 2022). Growth in water demand is expected to increase stress on water resources in the region. For instance, limitations in meeting demand are projected for the Washington DC areas in future demand projections for 2035 and 2040 (Ahmed et al., 2015). Between 2020 and 2040, total non-power demand is projected to increase by 21%, 14.5 m^3/s (332.32 MGD), with 73% coming from surface water (VDEQ, 2022). More than 11.4 m^3/s (260 MGD) of that 14.5 total projected increase is from public water supplies. While studies have been performed to assess the hydrological impacts of climate change (Baran et al., 2019; Sridhar et al., 2019) and increasing demand (Haddeland et al., 2014; Heidari et al., 2021; Schewe et al., 2014; Vörösmarty et al., 2000), the potential impacts of withdrawals that are exempt from permitting requirements are relatively unknown. With the increase in population and climate change, the exempt users may potentially withdraw more water to meet demands.

The objective of this study is to quantify the potential impact of permit-exempt water withdrawals on water supply during periods of low streamflow compared to impacts associated with climate change and increasing demand. To do this, we leverage a dataset of reported water withdrawals from 1051 surface intakes across VA, 63% of which are exempt from water supply permitting. We evaluate different methods for estimating the maximum amount of water that a permit-exempt user could withdraw and assess the impact of these claimed withdrawals using a comprehensive, modular flow model. We quantify the impact of permit-exempt withdrawals in terms of changes to 30- and 90-day low streamflows as well as average surface flows throughout the year. These impacts are compared to those resulting from projected increases in water demand across the state and a drying climate change scenario taken from an ensemble of 31 general circulation models (GCMs).

2 | METHODS

2.1 | Study area

Virginia provides a representative case study for the mid-Atlantic region. VA receives an average annual rainfall of around 1092 mm and stretches from the Appalachian Mountains in the west to Chesapeake Bay in the east along the Atlantic Coast. The majority of river basins in VA drain into the Chesapeake Bay, the largest estuary in the U.S. and the focus of extensive restoration efforts since the 1980s. The topography in VA varies from sea level at the east coast to course rugged mountain valleys with the highest peak of 1746 meters in the west. This topographic variation plays a vital role in determining the land use, development, and magnitude of streamflows in the region. Land use in VA is varied, with highly urbanized regions along the I-95 corridor in the eastern part of the state and agricultural and forested areas throughout the rest of the state. VA is rich in water resources with 80,500 km of non-tidal streams and rivers and 248 publicly owned lakes (owned lakes and reservoirs that serve multiple uses such as recreation, energy, etc.). Additionally, VA has about 955 km^2 of tidal and coastal wetlands, roughly 3269 km^2 of freshwater wetlands, 193 km of Atlantic Ocean coastline, and upwards of 7251 km^2 of estuaries (VDEQ, 2018).

This study was conducted for non-tidal portions of the Chesapeake Bay watershed within VA (Figure 1). This study area was chosen because it has detailed data available on permit-exempt water withdrawals, projections of water demand through 2040, and surface water runoff projections under multiple climate change scenarios. In addition to our broader analysis, the Dry River segment in VA was selected for a more detailed exploration of inter-annual flow trends under each scenario. The Dry River is located in the Shenandoah Valley portion of VA, ultimately flowing into the Shenandoah and Potomac Rivers. It begins in the George Washington National Forest and then flows through predominantly agricultural land before flowing into the North River near the town of Bridgewater, VA.

2.2 | Data sources

2.2.1 | Water withdrawal data

All water users who withdraw greater than 37.6 m^3 (10,000 gallons) in a single month are required to report monthly water withdrawals to VDEQ. The yearly data reported to VDEQ contains the facility name, facility type, location (latitude-longitude of intake or facility), withdrawal

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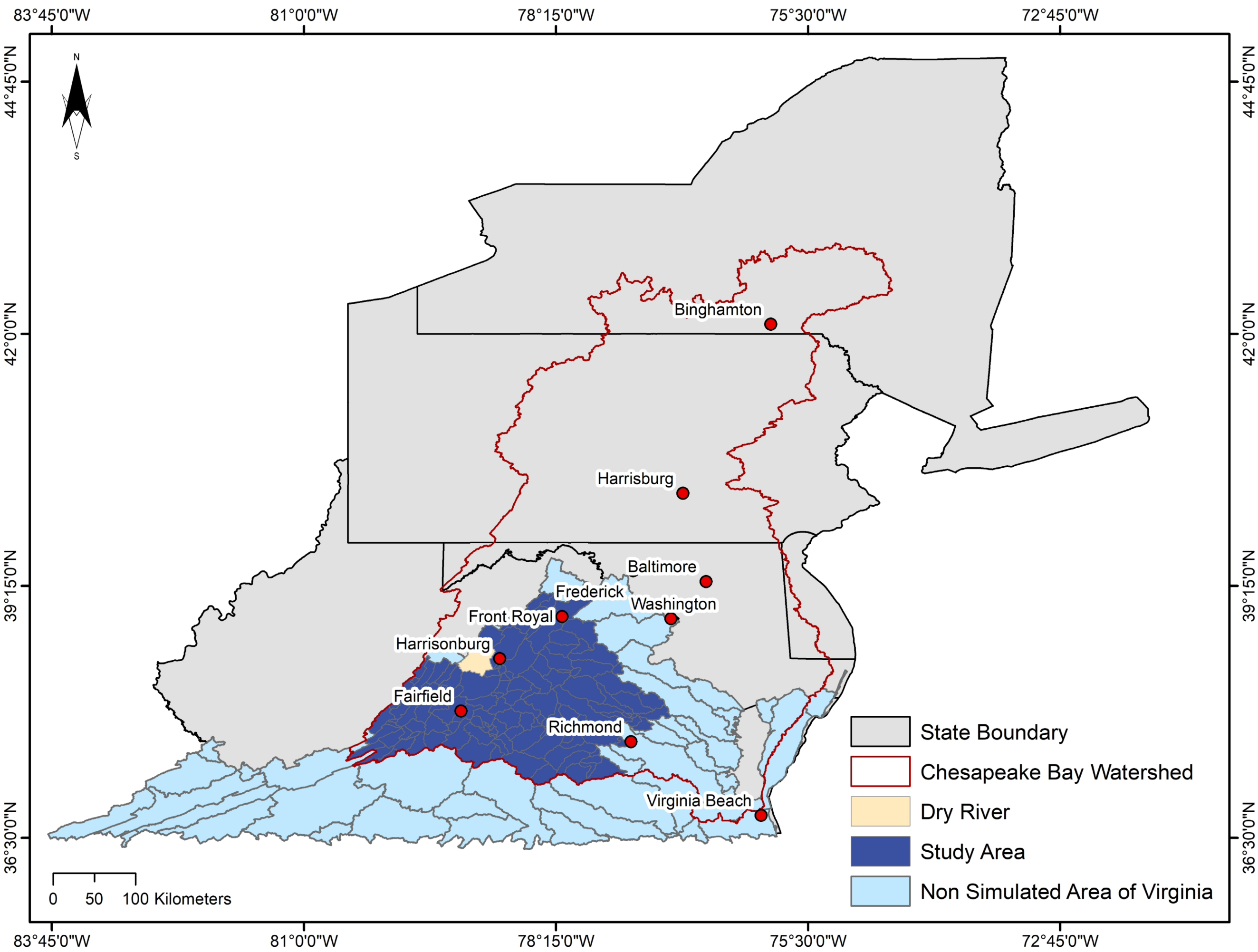

FIGURE 1 Study area non-tidal region of Virginia in Chesapeake Bay Watershed.

source, withdrawal amount, and withdrawal capacity of exempt user estimates from multiple data categories. Because the minimum volume requiring permitting and reporting of water use is 10,000 gallons per day, this excludes many small water users, including domestic wells used for household drinking water purposes. While a large number of small withdrawals can have a meaningful impact on cumulative water use (Sangha & Shortridge, 2023), the lack of data on their water withdrawal volumes necessitated that they be excluded from this study. The reporting categories for facility type include agriculture (livestock, fish farming, and hatcheries), commercial (golf courses, local and federal installations, hotels, resorts, and correctional centers), irrigation (row crops, vegetables, turfgrass, and ornamental nursery products), mining (excavation, processing, and removal of bulk products), manufacturing (paper mills, food processors, pharmaceutical companies, furniture), public water supplies, hydropower, fossil fuel and nuclear power for power generation. Non-exempt users must report withdrawals from all intakes, which are points from which water is extracted from either surface water or groundwater bodies. These withdrawal data are stored in the VDEQ's VAHydro, a comprehensive web-based platform that links water resource data with analytical and program administration tools. VAHydro includes over 1.3 million records of monthly water withdrawals from both surface and groundwater dating back to 1982. Because withdrawal data are stored as a monthly total, these monthly values are disaggregated to daily withdrawals by dividing the monthly total by the number of days in the month to use within water resource models applied within Virginia. While VAHydro is a dynamic, regularly updated system, this analysis used the withdrawal data as prepared for the 2020 Virginia State Water Resources Plan in December of 2019.

2.2.2 | Permit exemption data

Of the 1051 intakes reported in VAHydro, 84 of them are permitted, 662 are exempt from obtaining a permit because they were in place before 1989, and 305 are small withdrawals (<1 million gallons (3785 m^3) per month for agricultural withdrawals and below 300,000 gallons

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(1135 m^3) per month for non-agricultural users) which do not meet the permitting threshold. Each owner or operator of a surface water withdrawal system, whether permanent or temporary and subject to the specified exclusion criteria, is mandated to submit essential information to DEQ. For permanent systems, this comprises the intake structure's estimated maximum capacity, the existing intake structure's location, and any other data deemed necessary by the department. For temporary systems engaged in agricultural withdrawal, the submission should include the maximum annual surface water withdrawal data for the past 10 years. The timeframe for providing this information is within 1 year from the receipt of DEQ's request, and updates must be promptly supplied in case of any changes to the maximum capacity of the intake structure. The VAHydro system includes data on potential claimed volumes for permit-exempt users from seven different permit-exempt data categories, which are sourced from both required and voluntary reporting by users, as outlined in the VWP regulations (9VAC25-210-310) and VDEQ outreach:

- Requests for Information (RFI) withdrawals: Amendments in 2007 required exempt surface water users in Virginia to report withdrawals to VDEQ through RFIs, including information such as the estimated maximum capacity of the intake structure and the location of the existing intake structure and 10-year maximums for agricultural uses.
- Intake capacity: The estimated maximum physical flow capacity of the intake structure in place as of July 1, 1989, as reported by the facility in reply to the 2007–2008 RFI.
- Virginia Department of Health (VDH) pumping capacity: The maximum physical capacity (in MGD) of the water pumping mechanism reported in VDH Waterworks Operations permits issued for the facility.
- Withdrawals before July 1, 1989, monthly and yearly: The maximum annual and monthly water withdrawal reported before July 1, 1989.
- Safe yields 1985 and 2005: The highest water withdrawal amount during a Drought of Record, calculated as the lowest single-day flow occurring every 30 years (1Q30). Safe yield volumes were determined in 1985 and 2005, representing the 1Q30 volume based on USGS gage records.

A key challenge in estimating the impact of permit exemptions on water supply is uncertainty in the volume of water to which a permit-exempt user could claim a right to use. Not all permit-exempt users have withdrawal capacity of exempt users from all the data categories above; for instance, almost all permit exempt intakes have an associated pre-1989 withdrawal value but only 68 have a safe yield value. If an intake reported more than one exemption amount (e.g., both VDH pumping capacity and Intake capacity), the maximum exemption volume was selected from the permit-exempt data categories for use in flow modeling. All permit exempt data categories were to represent exempt withdrawals for modeling purposes.

2.3 | Simulation model

This study uses the VAHydro-model, a comprehensive, modular hydrological model used for water supply planning and permitting in VA. VAHydro is a multifaceted framework designed to establish interconnections among several specialized modules of water management. These modules encompass critical areas such as water withdrawal permitting, water supply planning, water withdrawal reporting, groundwater well registration, and drought monitoring and modeling for both surface water and groundwater dynamics. This model simulates river flows based on runoff generated by the Chesapeake Bay Watershed Model (CBWM) of the Chesapeake Bay Modeling System (CBMS). The fundamental hydrological response units in CBWM are land-river segments formed by the overlapping regions of land and river segments. Land segments are formed based on county lines, and river segments are derived from large rivers with a mean annual flow greater than 100 cfs. For each land and river segment, the CBWM uses rainfall, land use, and estimated evapotranspiration to generate infiltration, runoff, groundwater flow, interflow, and storage at an hourly timestep (Brogan et al., 2021); the resulting flow values are then calibrated across 272 USGS gages. Each river segment in the CBWM within Virginia has a corresponding feature in the VAHydro system. VAHydro-model takes hourly rainfall, evapotranspiration, and runoff from the calibrated CBWM as an input. VAHydro-model converts the overall unit runoff for each land use to the overall volume of runoff in each land-river segment. Runoff is either routed via the Muskingum method in the channel or by the Modified Plus method through an impoundment using a user-defined stage-storage-discharge relationship (Brogan, 2018; Hildebrand, 2020). Each river segment in the VAHydro-model is linked to local withdrawal facilities and surface water intakes. It should be noted that groundwater withdrawals and hydrology are modeled in a separate component (VAHydro-GW), which simulates groundwater dynamics in the heavily utilized coastal plain aquifer underlying the Eastern Virginia and Eastern Shore Groundwater Management Zones. Thus, this study does not consider issues such as the impact of groundwater pumping and interactions between surface and groundwater. However, 90% of water withdrawals in the state are from surface water sources, and the majority of groundwater withdrawals are from eastern parts of the state outside of our study area (JLARC, 2016).

VAHydro-model uses data from the linked parameters such as channel characteristics, withdrawals, discharges, land use data, runoff for each land-river segment, precipitation, and evaporation time series to simulate flows at daily timestep. Different methodologies are used in the VAHydro-model to estimate the consumptive use fractions to measure return flow to the streams. For the municipal sector, the consumptive

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use fractions are estimated by the winter base rate method and standard transmission loss of 10%. This method is often used in regions where water consumption activities are minimal during winter months (Li et al., 2017). The consumptive use fraction is based on the winter base method for VA. Other consumptive use factors were derived from literature based on facility type to estimate the amount of water used, such as 0 for Aquaculture, 1 for Agriculture and Irrigation, 0.1 for Industrial and Commercial, with 0 representing all water returned to the stream, and 1 means no water returned to the stream (McCarthy et al., 2022).

The flow is returned to the stream by subtracting the consumptive use from the withdrawals at the next downstream river segment or to the known outfall location (Figure 2). VAHydro-model also captures inter-basin transfers where return flows occur in a different watershed from their associated withdrawal. Consumptive use fractions remain constant over the years for a given scenario and may result in overestimation of consumption in wet years and underestimation of withdrawal in drought years especially in the areas of no low-flow withdrawal restrictions. VAHydro-model is then used to simulate surface water flows at daily timestep under different user-defined scenarios with respect to withdrawals (current, prospective water withdrawal permits, 2040 demands, exempt users withdrawals) and flows (climate change scenarios). VAHydro-model climate change scenarios were run only for non-tidal streams in VA that drain into the Chesapeake Bay.

2.4 | Scenario simulations and flow analysis

This study compares a base scenario representing current conditions with three alternative scenarios that represent long-term stressors to water supply: climate change, predicted 2040 demands, and exempt withdrawals. The hydrological model flow outputs temporally span from January 1, 1990, to December 31, 2000. The base scenario represents current precipitation and temperature conditions, uses current 2020 water demands as submitted by local and regional water supply plans and simulates the withdrawal amounts in recent years for permit-exempt users. This scenario was used as a baseline for comparison with the three other scenarios. For the future 2040 demand scenario, 2040 demands submitted by local planning entities were used with current meteorological conditions. The climate change scenario used 2040 water demands and the 10th percentile of temperature and precipitation from representative concentration pathway (RCP) 4.5, representing drier climatic conditions predicted by the GCMs of the 31-member ensemble obtained from the Chesapeake Bay Program (CBP). Thus, this scenario included the combined effects of a potentially dryer climate and higher future demands. Finally, in the exempt users scenario, maximum water allocation amounts were used with current meteorological conditions. The following sections describe each of these scenarios, along with the process used for comparing their impacts, in more detail.

2.4.1 | Exempt users scenario

The exempt user scenario examined the water resources impact of each permit-exempt intake withdrawing its maximum possible withdrawal capacity of exempt user. The user-reported withdrawal data contained a combination of withdrawal limits originating at the intake or facility level. Each record in the exemption database was determined and annotated as a facility limit or an intake level derived limit. It was ensured that all intakes were maximized, but if they have an intake level limit, it is not exceeded. The exempt demands in this simulation frequently exceeded available streamflow. The VAHydro stream simulation was updated to keep the hydrological balance for any time withdrawals exceeded channel flow.

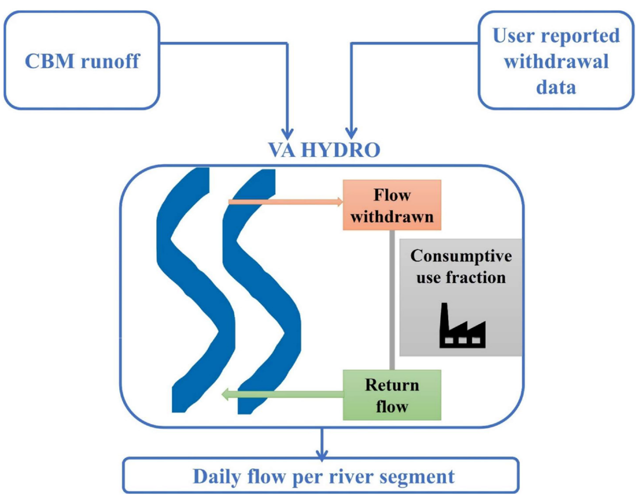

FIGURE 2 Conceptual overview of VAHydro modeling process. CBM, Chesapeake Bay Modeling.

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In such cases, stream withdrawals were set equal to river segment inflow during that time step. For modeling purposes, small intakes with withdrawal volumes less than the permitting threshold were simulated using current withdrawal volumes in the 2020 Virginia State Water Resources Plan, as shown in Figure S1. For permitted intakes, withdrawal volumes were based on the maximum permitted withdrawal volume based on either a VWP permit or 401 certifications (federal permit issued for an intake resulting in a pollutant discharge into U.S. waters) (Figure S1).

2.4.2 | Future demand projections

The 2040 demand scenario was used to analyze the impacts of the expected demand increase on VA water resources by 2040. Projections for 2040 demands are submitted to VDEQ by local and regional planning entities in the state. These entities are required by law to include future water demand in the regional water supply plan for a minimum of 30 to a maximum of 50 years into the future. The population projections in the local planning areas are developed using the U.S. Census Bureau, Bureau of Economic Analysis, VA Employment Commission, and local or regional sources. The demand increase for a particular intake was based on individual intake demand projections for 2040. Consumption amount was based on facility type and assumed to be the same for future projections. The demand projections were provided by localities in local and regional water supply plans submitted to VDEQ between 2011 and 2013. Some demand projections were updated in 2018 as part of the water supply plan review and included newly developed or updated water demand projection information from a variety of localities, water users, and stakeholders.

2.4.3 | Climate change projections

Climate change projections used in the study were obtained from the CBP. The CBP has conducted ongoing research on climate change impacts in the Chesapeake Bay watershed since 1983 (e.g., Najjar et al., 2010; Pyke et al., 2008). This study used runoff projections developed by the CBP to ensure that projections were based on rigorous and current methodologies. Projections were based on the CMIP5 climate model ensemble using the RCP 4.5. RCPs describe concentrations of greenhouse gases resulting from different human responses to climate change. RCP 4.5 is a stabilization scenario that considers the climate policies that are invoked to limit emissions and radiative forcing (Thomson et al., 2011; van Vuuren et al., 2011). Research indicates that RCPs 2.6, 4.5, and 8.5 show similar trajectories around the year 2055, aligning with the climate scenario range of 2040–2070 examined in this study (Tebaldi et al., 2021). In the RCP 4.5 scenario, emissions reach their highest point around 2040 and then begin to decrease, providing a moderate pathway for studying the effects in a scenario of medium intensity. CBP uses an ensemble of 31 downscaled GCMs to represent future climatic conditions for temperature and precipitation over the 2040–2070 timespan. This ensemble projects changes in temperature ranging from +0.9 to +3.2°C and changes in precipitation ranging from −1.3% to +20.1% across VA by midcentury. The climate change scenario used 10th percentile of temperature and precipitation from CBP's 31-member GCM ensemble for RCP 4.5. This scenario of RCP 4.5 entails a change in annual temperature and precipitation of 1 to 1.25°C and −11% to −7%, respectively, from the base scenario in VA. This reflects the potential for drier conditions within RCP 4.5 and helps study the impacts on water resources and the occurrence of low-flow conditions.

2.4.4 | Scenario analysis and comparison

These three alternative scenarios were each simulated independently from each other to assess the relative impact that each stressor would have during low-flow periods when meeting water demands is challenging. Thus, they are not meant to represent a view of what is likely to occur in the future, which would likely entail some combination of the three stressors included in our evaluation, as well as others. Instead, our analysis aims to quantify the relative sensitivity of water supply to each of these stressors and suggest which should be prioritized for additional research or planning interventions. Scenarios are aimed to represent a plausible trajectory of future demand changes, acknowledging that climate change and changing water demand are intertwined challenges.

Assessment of low flows is crucial for drought studies, water supply system management, estimation of safe water withdrawals, and evaluation of the stream's waste assimilation capacity (Ceylan & Lall, 2017; Smakhtin, 2001). The impact on low flows was evaluated at a daily timestep using 30-day low flow (L30) and 90-day low flow (L90) metrics and plotted at the river segment scale. L30 and L90 are calculated as the minimum 30-day rolling average and 90-day rolling average flow, respectively, over the simulation period. L30 and L90 flows help to indicate the short- and long-term resilience of water resources, respectively (Khaliq et al., 2008; Smakhtin, 2001). Reduction in L30 flows would likely impact users without access to reservoir or storage water, but the reduction in L90 flows would be detrimental for all users. The percentage difference for 30-day low flows and 90-day low flows was calculated between the base and each scenario using Equation (1), where the flow Change Scenario equals the L30 or L90 flow value calculated for that scenario,

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$$\text{Percentage Change} = \frac{\text{Flow}_{\text{Scenario}} - \text{Flow}_{\text{Base}}}{\text{Flow}_{\text{Base}}} \times 100. \tag{1}$$

In addition to the statewide low flow analysis, a single river segment (Dry River) was used for a more detailed investigation into the impact that each scenario had on temporal characteristics of the flow regime across the full year. The reduction in daily flows was examined by visualizing differences in flow duration curves (FDCs). Average monthly flows were calculated for each scenario to quantify the seasonal impact of permit exemptions relative to climate change and demand growth. These impacts were quantified by percentage and absolute difference. The percentage difference quantified the change in flow relative to initial flows in a base scenario using Equation (1). In addition to percentage change, the absolute difference in flows quantified the actual size of reduction in flows between two scenarios calculated at a monthly time step (Equation 2). Geographic patterns in flows change under different scenarios were calculated at the river segment scale and plotted using Tmap package in R (Tennekes, 2018),

$$\text{Absolute change} = \text{Flow}_{\text{Change}} - \text{Flow}_{\text{Base}}. \tag{2}$$

3 | RESULTS

3.1 | Statewide exempt users data

A total of 662 exempt intakes reported a cumulative withdrawal rate of 710 m^3 per second, which corresponds to approximately 16.2 billion gallons per day. The highest number of exemptions were based on pre-1989 monthly withdrawals, and intake capacity accounted for the highest volume of exempt withdrawals. The mean was higher for all the permit-exempt data categories than the median, indicating higher withdrawals accumulated by few intakes (Table 1).

It was found that 118 out of the total 133 counties and independent cities in Virginia have permit-exempt water withdrawals, underscoring the widespread nature of these exemptions (Figure 3a). In VA, exempt withdrawals constitute 76% of total withdrawals in each of the 133 counties and independent cities (Figure 3b). The largest numbers of exemptions are used for irrigation, but these only account for a small volume of total exempt water use. The largest volumes of exempt water withdrawals stem from the municipal and manufacturing sectors. Table S3 summarizes the exemption amounts among the different water use sectors of agriculture, commercial, industrial, energy, irrigation, manufacturing, mining, and municipal. In Table S3, fossil power represents a subset of energy withdrawals.

3.2 | Statewide L30 and L90 results

Reductions in flows were observed in multiple land-river segments in Virginia under different scenarios, including climate change, exempt users, and 2040 demands, exhibiting varying geographical patterns (Figure 4). Findings show 41% of land-river segments in VA experience

TABLE 1 Summary of exempt users data availability and limits by permit exempt data categories.

	Safe yield 1985	Safe yield 2005	Requests for information withdrawals	Pre-July 1989–withdrawals monthly	Pre-July 1989–withdrawals yearly	Intake capacity	VDH pumping capacity
Total reporting intakes[a]	68	57	153	568	570	237	134
Number of exemptions used for modeling[b]	17	14	132	303	7	133	56
Min (m^3/s)	9.1E-02	6.2E-02	3.0E-05	1.0E-04	2.0E-05	2.0E-05	9.0E-03
Mean (m^3/s)	2.063	3.755	1.914	0.370	0.024	1.735	0.481
1st Quantile (m^3/s)	0.140	0.193	0.001	0.003	0.003	0.033	0.088
Median (m^3/s)	0.442	0.458	0.004	0.010	0.008	0.076	0.176
3rd Quantile (m^3/s)	4.073	1.201	0.044	0.039	0.032	0.263	0.439
Max (m^3/s)	9.943	19.530	173.700	41.850	0.089	87.600	3.590
Total volume of exemptions (m^3/s)	35.07	52.57	252.63	112.18	0.17	230.74	26.91

[a]Total reported intakes are the number of intakes reporting to VDEQ. One intake may report exemption for more than one data source.

[b]For modeling, the highest exemption amount from the multiple permit exempt data categories was selected and marked as "Number of exemptions."

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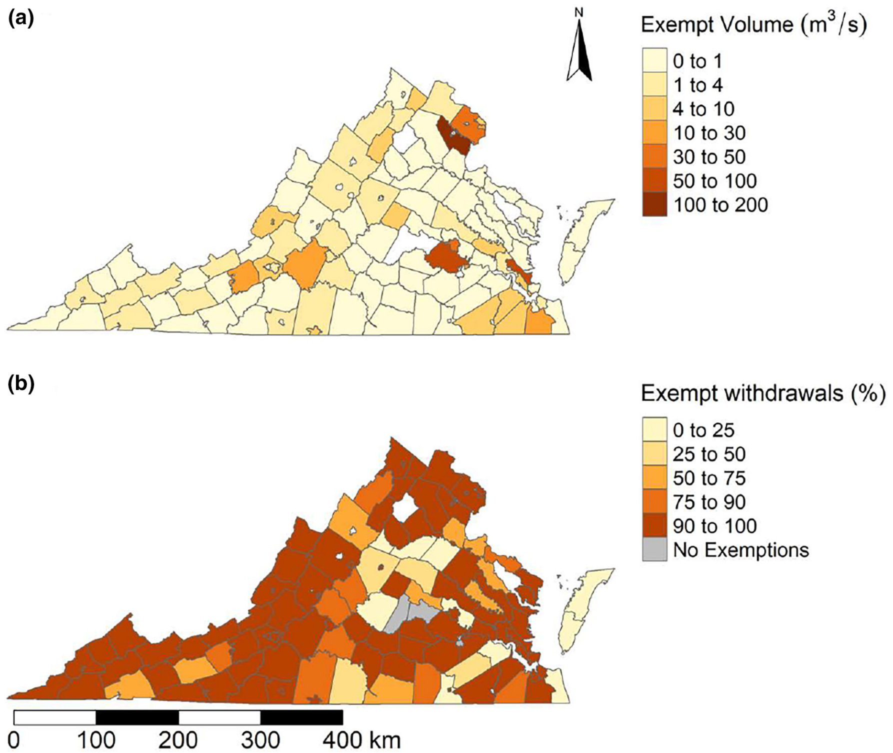

FIGURE 3 Sum of county-level exempt withdrawals (m^3/s) in Virginia(a) and percentage of total withdrawals in each county exempt from permitting (b).

some reduction in L30 flows for the 2040 Demand Scenario, while 96% and 74% of VA land river segments experienced some reduction in L30 flows under the climate change and exempt users scenarios, respectively (Figure 4). Similarly, for 90-day low flows, 42%, 99%, and 70% of the VA's land-river segments experienced a reduction under the 2040 demands, climate change, and exempt users scenarios (Figure 4). Water withdrawals are projected to decline, resulting in a relative decrease in 30- and 90-day low flows for 27 river segments. Geographically, the climate change scenario results in widespread declines in 30- and 90-day low flows, whereas the impacts from permit exemptions and 2040 demands are more localized (Figure 4b,e).

Figure 5a,b show density plots of the percentage change in L30 and L90 flows in the 2040 demand, climate change, and permit exemption scenarios relative to the base scenario across the 127 land-river segments included in the simulation. The distribution of changes under the 2040 demand scenario ranges from −52% to +26% and has a mean change of −1.5%. However, the majority of land-river segments experience only minor changes in 30-day flow under this scenario, with 88% of land-river segments falling between −10% and +10% (Figure 5a). In the climate change scenario, the percentage change in L30 flows varied from −74% to +15%, but most (96%) were negative, and the mean change was −30%. However, in exempt users scenarios, the percentage difference in L30 flows varies between −100% in L30 flows on the lower end and +34% on the higher end. Therefore, while the mean change in flow under the permit exempt scenario (−23%) was not as severe as the climate change scenario, the impact in certain locations was far more severe.

Similar trends were observed for L90 flows (Figure 5b), with the 2040 demand scenario mostly resulting in minor changes, the climate change scenario resulting in widespread declines, and the permit exemption scenario resulting in a lower average change but a wider range of impacts across land-river segments. However, the range of changes to L90 flows under the climate change and permit exemption scenarios was narrower than the corresponding range of changes to L30 flows. For 2040 demands, changes ranged from −41% to 24%, while changes in the climate change and exempt users scenarios ranged from −52% to 0% and −97% to +18% respectively for L90 flows. The magnitude of the percentage change was highest in the exempt users scenario, with 18% and 11% of the land-river segments experiencing more than −50% reduction in L30 and 90 flows as compared to 9.0% and 0.78% of land river segments under climate change scenario and 0.78% and 0% of land river segments in the 2040 demand scenario.

3.3 | Dry River case study

While the statewide results focused on impacts specifically to L30 and L90 flows, the three scenarios evaluated are likely to result in impacts across the range of flows experienced. To understand these impacts, the Dry River was used as a case study and FDCs were plotted for each

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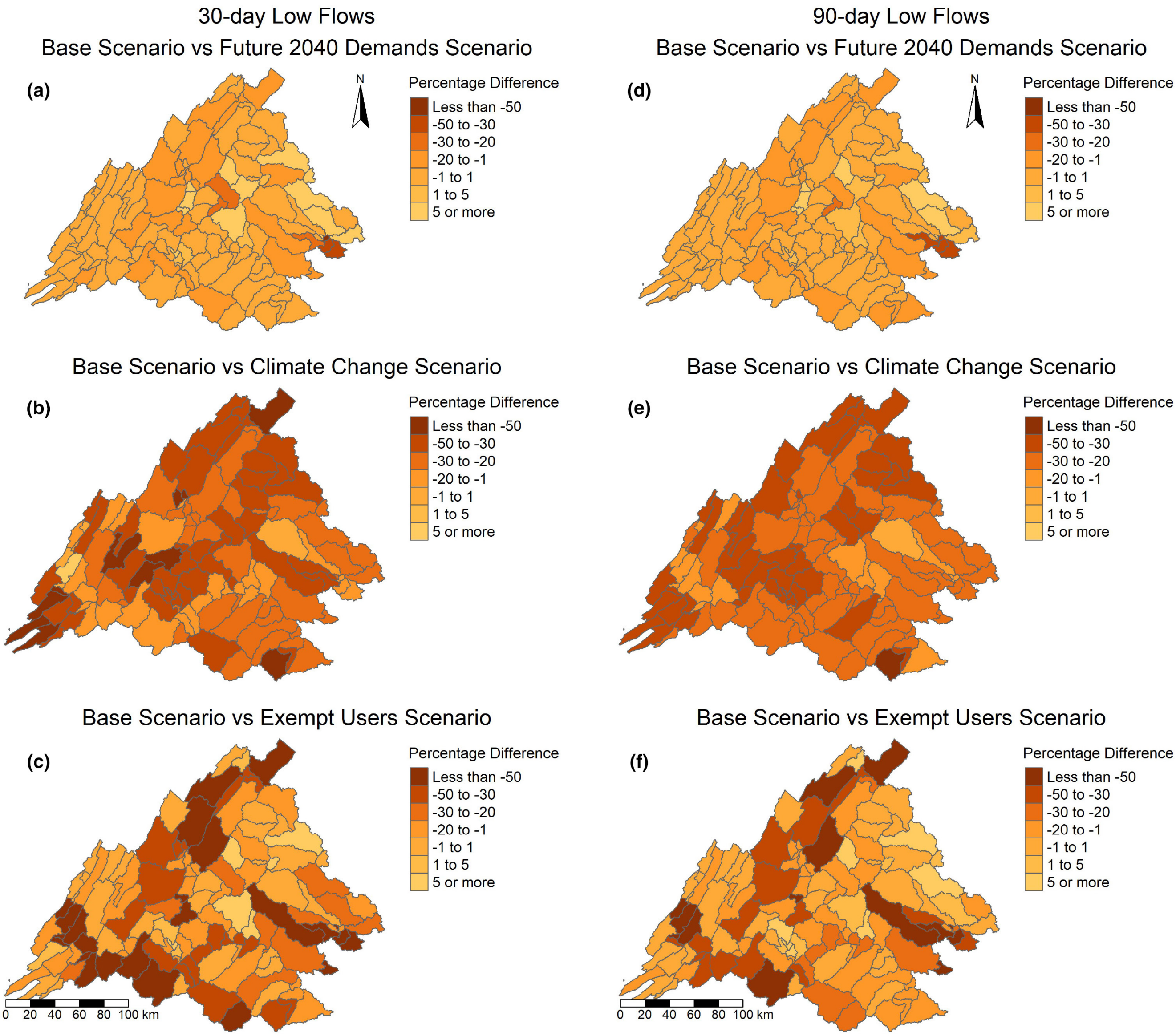

FIGURE 4 Percentage difference in 30-day low flows between baseline and (a) 2040 demand scenario, (b) climate change scenario, and (c) exempt users' scenario and for 90-day low flows between baseline and (d) 2040 demand scenario, (e) climate change scenario, and (f) exempt users' scenario.

of the three scenarios (Figure 6). A decline in flows was observed in all three scenarios. Dry River segment observed a L90 flow reduction of 18%, 33%, and 44% in the 2040 demand, climate change, and exempt users scenarios, respectively. This compares to mean reduction in L90 flow across all segments statewide of −1.1%, −27% and −15% in the 2040 demand, climate change and exempt users scenario, respectively. A significant drop in flow was observed at extreme high flow events (exceedance probability of 0% to 1%) in the climate change scenario from the base scenario. The reduction in flow for these extreme events was minimal for the 2040 demand scenario and small for the exempt users scenario. Similar reductions were observed under all three scenarios for high flow (exceedance probability between 1% and 10%). However, for medium flows (exceedance probability between 10% and 70%), the flow declined for both climate change and exempt users. For low flows with probability exceedance between 70% and 100%, the reduction in flows was highest for the exempt users scenario, falling below the flows in the climate change scenario. Similarly, in extreme drought events (probability exceedance between 95% and 99%), exempt users scenarios saw the highest reduction in flows. Overall, the 2040 demand scenario primarily impacted low flows, whereas, in the climate change scenario, a higher reduction was observed throughout the flow regime. The exempt users scenario impacted medium to low flows and impacts surpassed the climate change scenario at low and extreme drought conditions.

To understand seasonal impacts on flow under each scenario, the percentage and absolute changes to average flow in each calendar year were compared (Figure 7). On the monthly time step, the most severe flow reductions in terms of percentage changes were observed from

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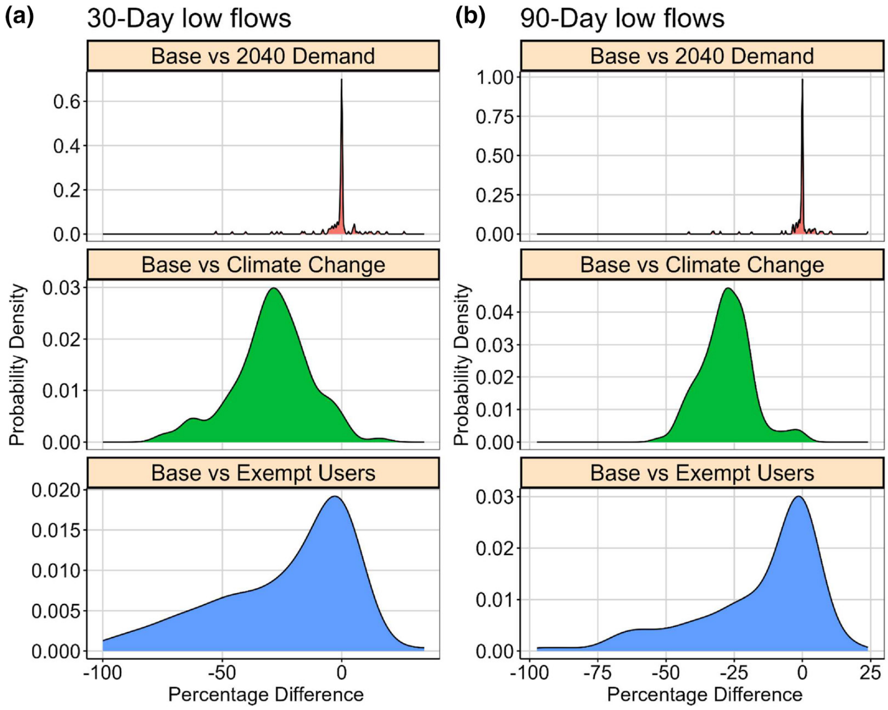

FIGURE 5 Probability density plot for percentage change in 30-day low flows (a) and 90-day low flows (b) under different scenarios across different river segments.

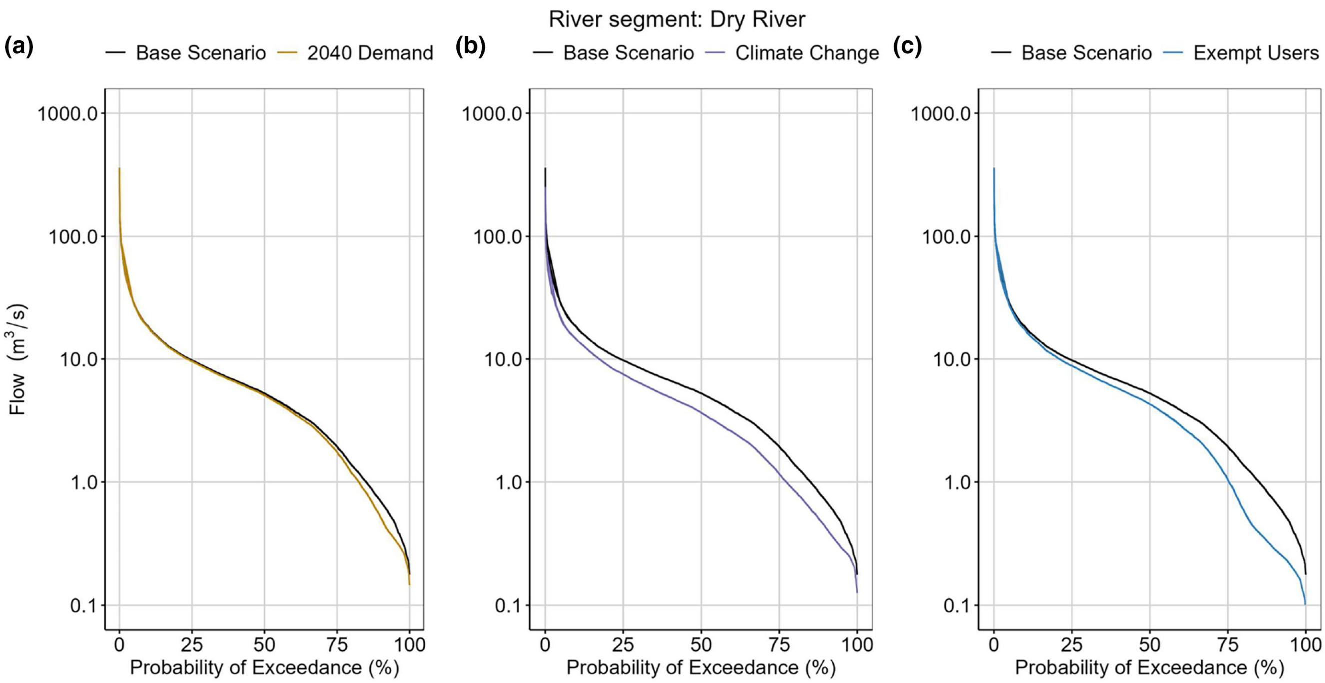

FIGURE 6 Dry river flow duration curve under different scenarios (a) Base vs 2040 Demand (b) Base vs Climate Change (c) Base vs Exempt Users.

July to November for all three scenarios (Figure 7a). However, the late summer and early fall is the period when flows across VA are lowest, so these large percentage changes do not necessarily lead to large declines in the absolute volume of streamflow. Declines in absolute flow were greatest in the winter months under the climate change scenario and the winter and spring under the permit exemption scenario while being consistent across the year for the 2040 demand scenario (Figure 7b).

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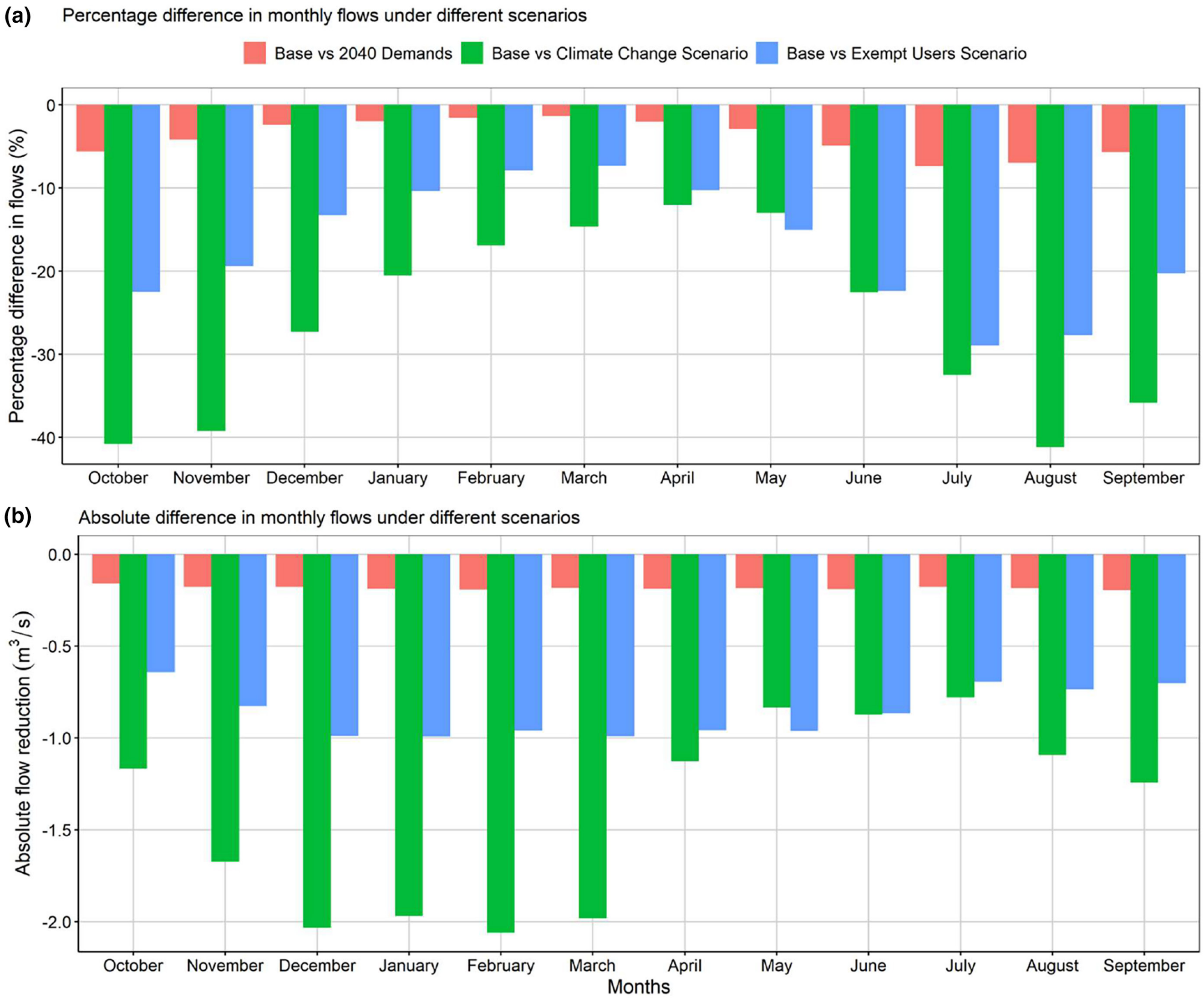

FIGURE 7 Percentage difference (a) and absolute difference (b) in monthly flows under each scenario for dry river segment.

4 | DISCUSSION

The examination of the user-reported exempt users dataset showed the scale of the exempt users in VA. This initial examination of exempt users indicated a high prevalence of such users across the state. The user-reported data showed that high exemption amounts exist in VA counties with at least some exemptions in 121 of 133 total counties and independent cities in VA. These exemptions also span over all permit-exempt data categories (Table S2) and water use categories (Table S3) and represent a large portion of water used overall. This poses a significant challenge to water resource planning in the state, as it encompasses diverse water use sectors. Focusing solely on one sector would not suffice to effectively address the issue of exempt water users (Shortridge & DiCarlo, 2020; VDEQ, 2018). Many other states have exemptions to their permit requirements similar to, or even more lenient than, those that exist in VA, and may not have the benefit of reporting regulation such as VAC (1990). These observations suggest the potential for a similar existence of the widespread and high amount of exempt withdrawals. Local demographics also drive the exemption amounts. The exemptions were high in urban areas (Fairfax County, Loudoun County outside Washington DC, Richmond City), possibly due to rapid urbanization in both areas with high exemption amounts for the municipal and manufacturing sectors (Figure 3a). With future development projections, these areas pose a challenge to water security because as demands increase due to population or climatic factors, such areas would likely exploit a higher fraction of their allotted exemption amounts. At the time of water shortages, such users would find themselves at an advantage to withdraw water while other permitted users faced more stringent restrictions.

The impact on low flows was examined using 30- and 90-day low flows. The impact on 30-day low flows under these scenarios suggests acute stresses to water resources. This analysis helps inform water resource planning by identifying land-river segments at high risk of future

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alteration due to exempt users, potentially surpassing the impacts of climate change in certain locations. The impact of climate change was more widespread across the counties, indicating the combined impact of meteorological and land-use changes expected in VA. On the other hand, the exempt use impact was more intense at the specific locations with higher exemptions. Similarly, results were observed for 90-day low flows with widespread impacts in the climate change scenario, and localized but high impacts were observed for the exempt users scenario. The 30- and 90-day low flows take into account some storm runoff and snowmelt; therefore, the reduction in 30- and 90-day low flows indicates a higher impact during drought and low flow conditions (Holmstrom, 1980; Nasri & Modarres, 2019). In addition to water quantity, the impacts of low flows have been found to have significant implications for water quality. For instance, during a 30-day low-flow period, oxygen depletion has been observed in a severely infested section of a river (Effler et al., 1998). Such low-flow conditions play a crucial role in shaping the biotic composition, structure, and function of aquatic, wetland, and riparian ecosystems (Richter et al., 1996; Sangha, Lamba, Kumar, Srivastava, et al., 2020). Similarly, the 2040 demand scenario shows high reductions in flows in certain potential areas of high-water demand, while other locations where demand is projected to decrease see flow increases. This analysis shows the rules for current inclusion and exclusion for permit allocations have a vital role in water management. This points toward a potential need for geographically specific management requirements such as surface water management areas as in VAC, 1992. Such management practices for specifically designated areas already exist for identification of critical source areas, Best Management Practices and Total Maximum Daily Loads implementation under Section 303(d) of the Clean Water Act (Borah et al., 2006). Implementation of geographically specific management approaches could be appropriate in the areas specifically under water stress due to permit exemptions and projected increases in demand.

In general, the reductions in 30-day low flows became more severe with an increasing volume of exempt withdrawals (Figure 8). However, there were some notable exceptions to this general pattern. For example, the Mechums River segment has a large increase in withdrawals, from 0.002 m^3/s (0.054 MGD) in the base scenario to 1.5 m^3/s (35 MGD) in the exempt scenario, but no decline in L30 flows (Figure 8b). The Mechums River segment is located at the confluence of South Fork of Rivanna River. Therefore, the large increase in exempt withdrawals is accommodated by the high flows in the segment without impacts on L30 and L90 flows. On the other hand, some river segments were highly impacted even with a small increase in exempt withdrawals from base withdrawals. For instance, the North Anna River above Little River saw a reduction of 99% in L30 flows with only a minor increase in exempt withdrawal (134% exempt of base withdrawals). This was potentially due to flow impacts from the North Anna Dam upstream and demonstrates that exempt users in small volume when combined with permitted users may result in high impacts on L30 flows.

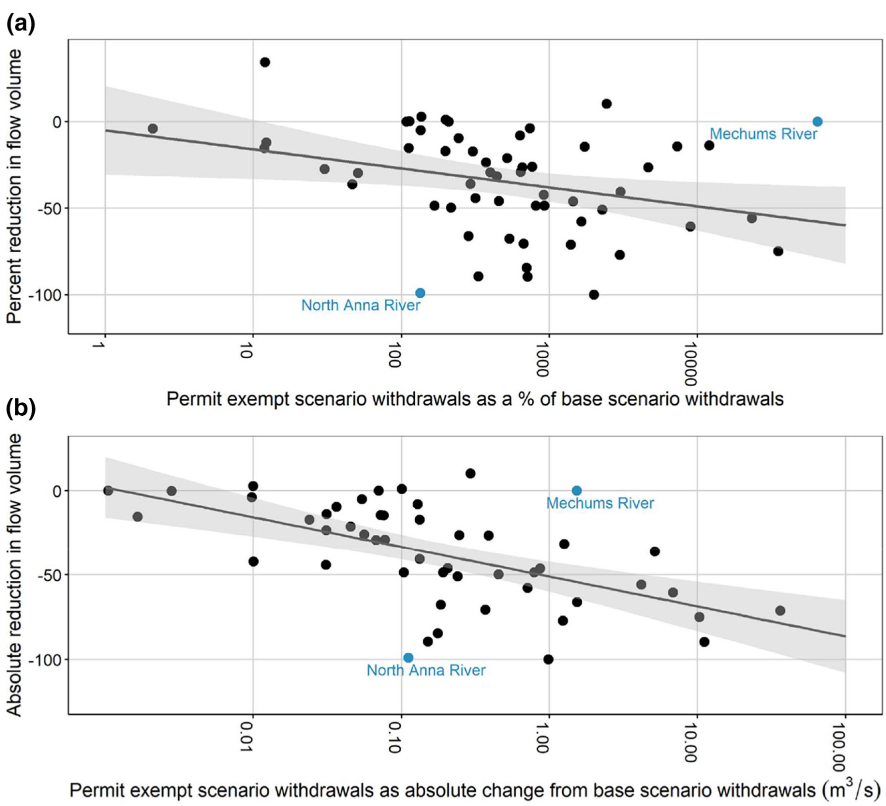

FIGURE 8 Change in low flow volumes (L30) in each river segment as a function of exempt withdrawal volume, presented as (a) a percentage change relative to base scenario and (b) an absolute change relative to the base scenario. A value of 100 in (a) indicates permit exempt scenario withdrawals are equal to base scenario withdrawals. Blue dots represent individual river segments discussed in the text.

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FDCs for the Dry River (Figure 6) show a reduction in flows across the hydrograph under the climate change scenario. However, the impact of exempt users surpassed the impact of climate change scenarios at low flow events. This affirms the notion that exempt users who don't need to adhere to any withdrawal restriction at the time of low flows pose a potential stress to the water supply at low flows. The percentage difference in flows and absolute difference in flows were high during the fall and winter for the climate change and exempt users scenarios and relatively smaller for 2040 demands (Figure 7). Under climate change scenarios, the flows were highly impacted in few months (December to March). In contrast, exempt users and 2040 demand growth impacts were observed throughout the year, interestingly close to climate change scenarios during summer months (April to July). Seasonality was observed in percentage differences with more difference in follows during August to November indicating the relative difference in the scenarios was higher in these months. If the extent of irrigated agriculture increases in the areas east of Mississippi, as some expect that it will (e.g., Walton, 2014), water demand in summer months may increase, resulting in higher impacts on low flows. This also indicates the need for management practices for inter-annual variability of flows and short-term droughts occurring within the year, especially during summer months at the time of high-water demand.

This study effectively shows that water resource stresses posed by permit exempt withdrawals are equal or greater to those from demand growth and climate change in many locations, suggesting a need for a prospective water planning that addresses these challenges, even in humid climates like VA. This study also emphasizes the need for water management policy beyond the streams' qualitative and quantitative aspects. The water management policies have been traditionally limited to professionals qualified in engineering, agriculture, and the hydrological sciences (Rey et al., 2019). However, in addition to policy amendments, this study advocates broadening community participation and awareness among users. The flow reductions resulting from demand growth and exempt users scenarios are highly influenced by user behavior. Adopting conservation practices and responsiveness among the users could result in a better understanding of users and influence user behavior at the time of water shortages to mitigate the impacts of low flows.

One of the key assumptions of this study was the full exploitation of the allocated exempt volume for water withdrawals by the users. In this study, the maximum withdrawal capacity of exempt users among the permit-exempt data categories was used to model the implications of permit-exempt withdrawals on VA's water resources. It is important to note that the maximum exempt volume does not represent the feasible maximum withdrawal volume at every given facility today or in the short term. The maximum withdrawal capacity of exempt users is, in part, a hypothetical volume caused by vagueness in the statute and represents entitlements that have been communicated to DEQ by various withdrawing facilities. Several of the permit exempt data categories come from VDH Waterworks Operation Permits, which determine maximum permitted waterworks capacity. Full realization of that withdrawal volume in practice may require additional capital investment in upgrading elements of the system, other than the intake, which may currently limit their ability to withdraw this maximum volume. Using the maximum exempt value serves as a useful upper endpoint for a ranging exercise to evaluate the potential water resources management implications of this unsettled legal question. However, even assigning minimum volume among permit-exempt data categories as the withdrawal capacity of exempt users results in withdrawals of over 222 m^3 per second; higher than the 2040 non-power demands (5 billion gallons per day; Table S2). Although the impact of minimum exempt water withdrawals was not examined here, the data suggest there is still potential for strain on water resources. Even if permit-exempt users only withdrew the smallest allowable amount, the cumulative effect could impact water supply. Further analysis is needed to quantify the risks at lower withdrawal volumes.

Many states require new water permits to be justified assuming whole allotted water as "used" (Sheer, 2010), but this may not always happen in practice. In the short term, exempt over-allocated users may not result in a gap between water demand and water supply but remains a red flag for potential conflict (Owen, 2014; Sangha, Lamba, & Kumar, 2020). However, due to the limited temporal extent of the model simulation, there is possibility for more extreme drought years which are not captured in this analysis. Therefore, extreme droughts could have a higher impact than depicted in this study. While this study focused on meteorological and user-reported data, future studies should consider the user behavior under various meteorological conditions. Additional research could quantify the cumulative impact of demand growth, exempt users and climate change. Analyses such as this can help highlight regions most at risk for water supply challenges stemming from permit exemptions, particularly if this information is presented in interactive tools or applications.

5 | CONCLUSION

Virginia, traditionally a well-off state in terms of water resources, has experienced increased pressure on its water resources over the recent years. This study uses VA as a representative case study for the Mid-Atlantic to assess the security of water resources in VA. This study acts as a stress test for increasing demands, low rainfall, and permit exemption statute using three scenarios reflecting future 2040 demands, "dry" future climate change, and exempt users. The study introduces the challenges posed by exempt users unrestricted by permit for making withdrawals at the time of low flows. The highest volume among various user-reported permit exempt data categories was selected for modeling purposes. While not analyzed in this study, this suggests that exempt users would potentially stress water resources even if they were to withdraw the lowest withdrawal capacity of exempt user from the permit-exempt data categories. The minimum volume reported by different permit-exempt user categories exceeded the 2040 non-power demands. If these users were to withdraw at the lowest capacity allowed by

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their exempt status, it could potentially stress water resources. Additionally, no single permit exempt data category contained the maximum exempt value for all facilities for exempt withdrawals, indicating a need for policy-driven management practices rather than a narrow focus on a single permit exempt data category. It was found that exempt users exist in 121 of 133 counties and independent cities in VA, totaling 710 m^3/s (16.2 billion gallons per day) of exemptions. To put this number into context, these exemptions total more than twice the projected 2040 demands (including power intakes) and more than eight times 2040 non-power demands. Similar regulatory exemptions for permitting exist in many other states such as Maryland, Connecticut, Georgia, Mississippi, South Carolina, Pennsylvania and more. It was determined that the uncertainty generated by the volume of water used by exempt users under different circumstances poses significant water supply planning and sustainability challenges. The unrestricted exempt withdrawals surpassed the impacts of dry climate change for low flows, indicating that the exempt users would highly impact the low flows if allowed to withdraw water at the exemption amounts. This study affirms the need for comprehensive water resource management policy and planning that addresses permit exemptions to mitigate low flows, even in humid states.

AUTHOR CONTRIBUTIONS

Laljeet Sangha: Data curation; formal analysis; investigation; methodology; visualization; writing – original draft. **Daniel Hildebrand:** Data curation; formal analysis; visualization; writing – review and editing. **Durelle Scott:** Conceptualization; funding acquisition; project administration; supervision; writing – review and editing. **Julie Shortridge:** Conceptualization; funding acquisition; methodology; project administration; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data and codes used in this study are publicly available through GitHub at https://github.com/laljeet/JAWRA-Exempt-Users-Manuscript.

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Additional supporting information can be found online in the Supporting Information section at the end of this article.

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