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Twenty-First Century Streamflow and Climate Change in Forest Catchments of the Central Appalachian Mountains Region, US

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Abstract: Forested catchments are critical sources of freshwater used by society, but anthropogenic climate change can alter the amount of precipitation partitioned into streamflow and evapotranspiration, threatening their role as reliable fresh water sources. One such region in the eastern US is the heavily forested central Appalachian Mountains region that provides fresh water to local and downstream metropolitan areas. Despite the hydrological importance of this region, the sensitivity of forested catchments to climate change and the implications for long-term water balance partitioning are largely unknown. We used long-term historic (1950–2004) and future (2005–2099) ensemble climate and water balance data and a simple energy–water balance model to quantify streamflow sensitivity and project future streamflow changes for 29 forested catchments under two future Relative Concentration Pathways. We found that streamflow is expected to increase under the low-emission pathway and decrease under the high-emission pathway. Furthermore, despite the greater sensitivity of streamflow to precipitation, larger increases in atmospheric demand offset increases in precipitation-induced streamflow, resulting in moderate changes in long-term water availability in the future. Catchment-scale results are summarized across basins and the region to provide water managers and decision makers with information about climate change at scales relevant to decision making.

Keywords: climate change; Appalachian Mountains; streamflow sensitivity; water security; water balance partitioning; Budyko

1. Introduction

Forested headwater catchments play a critical role in provisioning freshwater to humanity [1–3], but anthropogenic climate change can alter the amount of precipitation (P) partitioned into streamflow (Q), evapotranspiration (E), and storage [4]. Changes in Q from headwater catchments is of particular concern given the importance of mountain regions in generating fresh water [5,6], which is used by society for drinking and water-intensive production [7–9]. One such headwaters area in the eastern US is the central Appalachian Mountains region (Figure 1). This region provides water to local metropolitan areas including Pittsburgh, Pennsylvania; Charlotte, North Carolina; and Memphis, Tennessee and to downstream cities such as Washington, DC; Cincinnati, Ohio; Louisville, Kentucky; Atlanta, Georgia; and New Orleans, Louisiana [10]. Given the hydrological importance of this region, gaining an insight into the potential impacts of anthropogenic climate change on future Q is critical for developing policies and practices that enhance water security throughout the region [11,12].

Figure 1. Location map of the U.S. Geological Survey Hydro-Climatic Data Network (HCDN) catchments studied in the central Appalachian Mountains region.

Water availability at the land surface is the result of the balance between atmospheric water demand [12–14], described here as potential evapotranspiration (PET) and P . Atmospheric water demand is driven primarily by solar radiation, which supplies the energy required to vaporize liquid water [15,16]. The ratio between PET and P , called the aridity index (AI), describes how much P is partitioned and returned back to the atmosphere [17–19]. AI is a first-order hydro-climatological control since it describes the absolute amount of water that can be lost to evaporation.

Over the last several decades, this region has become warmer and wetter [20,21], theoretically consistent with water cycle intensification [22]. Air temperatures have increased, on average, by 1°C , or $0.09^{\circ}\text{C/decade}$ [23]. Precipitation has increased, on average, by $\sim 10\text{ mm/decade}$ [24], as have heavy downpours (events that are exceeded 1% of the time in any given year) which have increased by 71% in the Northeast and 37% in the Midwest over the last three to five decades [25]. In West Virginia, a small state that is geographically central to the region and representative of the topographical, ecological, and climatological gradients of the area [26], minimum and maximum air temperatures have increased by 0.15°C and $0.03^{\circ}\text{C/decade}$, respectively, while P has increased by 25 mm/decade since 1959 [26]. During the last half of the 20th century, mean annual Q , low flow, and base flow have all increased throughout the larger mid-Atlantic region [27–29]. Since 1951, the monthly Q throughout the region has increased by 1 to 2 mm/year , with the largest increases during the fall and winter seasons due to increases in precipitation [29]. Coincidentally, the forest growing season length throughout the region has increased on average by 22 days since 1983 [30] as has E , which has increased between 0.4 to 4 mm/year [30–32].

Fernandez and Zegre [16] quantified future changes in P and energy balance components for 420 counties and 13 states that comprise the Appalachian region, USA. The study found that both PET and P are projected to increase through the 21st century. P has been projected to become more variable through time; under Relative Concentration Pathways (RCP) 4.5 [33], where global atmospheric CO_2 emissions are stabilized by mid-century, P is projected to increase during the first quarter of the 21st century (2006–2025), progressively decrease through mid-21st century (2026–2075), and then increase again late in the century (2076–2099). Under RCP8.5, where global atmospheric CO_2 continues to increase unabated, P is projected to decrease early in the century, progressively increase through the

mid-century, and continue to increase in the northern extent and decrease in the southern extent of the Appalachians. PET, on the other hand, is projected to progressively increase throughout the 21st century by 5%–20% (RCP4.5) and 20%–35% (RCP8.5)—a rate greater than P [16]. AI is projected to increase at higher elevations, shrinking the areas of headwaters [16] that have historically been characterized as energy limited (i.e., P exceeds PET) [34,35] and are critical for maintaining downstream water availability [2,36]. Furthermore, P and PET are projected to become seasonally desynchronized, with P increasing during the dormant season and PET increasing during the growing season. Collectively, these changes have the potential to increase the occurrences of floods and droughts throughout the region [37–40], increasing the challenges of managing water resources under greater uncertainty and risk [36].

Despite the importance of this region as a freshwater source to local and downstream ecosystems and economies [10,39,41], the sensitivity of forested catchments to climate change, and the implications for long-term water balance partitioning, are largely unknown. Previous studies have focused on single catchments, mixed-use catchments, or larger regional scales (e.g., mid-Atlantic, mid-western, northeastern US; Chesapeake Bay) [37–39,42,43] but the uniqueness of place and variations in topography, geography, land use, and landcover limit inference for catchment-scale decision making.

In this study, we quantified water balance sensitivity to changes in future climate using a simple Budyko-based energy model [14] to provide insight into how fresh water provisioning from forested catchments throughout the region might change due to anthropogenic climate change. Specifically, we quantified streamflow changes at the catchment scale and summarized them across basins and the region to provide watershed and natural resource managers and decision makers with information about climate change at scales relevant to decision making.

The objectives of this study are therefore to (1) quantify streamflow sensitivity to historical changes in climate in minimally impacted catchments; (2) quantify future climate change at the catchment-scale throughout the region; (3) model future Q under two Relative Concentration Pathways to understand how future climate change might impact water resources availability throughout the region; and (4) evaluate spatial patterns of future streamflow sensitivity to climate.

2. Materials and Methods

2.1. Data

Mean daily streamflow were extracted for 29 catchments located across five dominant river basins across the region (Figure 1): the Monongahela, Upper Ohio, Kanawha, and Tennessee Rivers, which drain west to the Mississippi River and Gulf of Mexico, and the Potomac River, which drains east to Washington D.C. and the Chesapeake Bay. The 29 catchments represent 39% of the total area of the five river basins, with five catchments in the Monongahela, two in the Upper Ohio, six catchments in the Kanawha, three in the Tennessee, and 13 in the Potomac Basin (Figure 1). This largely forested region covers approximately 125,000 km² and spans across eight states: West Virginia (WV), eastern Ohio (OH), southwestern Pennsylvania (PA), eastern Kentucky (KY), western Virginia (VA), western North Carolina (NC), Maryland (MD), and western Tennessee (TN). Criteria for selecting the catchments were based on (1) inclusion in the U.S. Geological Survey Hydro-Climatic Data Network (HCDN) [44,45] and (2) a representative range of catchment areas (34–8101 km²) (Table 1). The HCDN consists of streamflow gaging station data for minimally impacted catchments (<10% human influence, e.g., reservoirs, diversion, land use change, or severe ground-water pumping) identified as a subset of the national-scale USGS gauging stations and developed specifically for the purpose of studying the variation in surface-water conditions throughout the United States [45]. The HCDN data set has been used in many hydro climatic studies [28,46–51]. We extracted Q data from the national USGS Water Data dataset (<https://waterdata.usgs.gov/nwis>) from 1965–2004. While the World Meteorological Organization (WMO) recommends 30 years of continuous data to calculate “climate normals” [52],

recent Budyko-based studies have used shorter time periods (e.g., 5–27 years) [51,53], based on the requirement of steady-state water balance conditions. [51].

A regional land cover analysis using the 2011 National Land Cover Database (NLCD) [54] was used to assess whether catchments still met the definition of being “minimally impacted” in the extended analysis period beyond the original NLCD. Q data were normalized by area (km²), converted to millimeters per year, and averaged to annual values using the USGS water-year (1 October–30 September).

Historic and future air temperature and P were extracted from the Multivariate Adaptive Constructed Analogs version 2 (MACAv2-METDATA) dataset [55]. MACA data are downscaled and bias corrected from Global Climate Models (GCMs) to a spatial resolution of gridded 4 km using non-parametric-quantile mapping and a constructed Analogs method [16,56]. The gridded climate values were averaged within the watershed boundaries. MACA only developed RCPs for 4.5 and 8.5, excluding 2.6 and 6.0 [3,57]. RCP4.5 represents a scenario in which greenhouse gas emissions are stabilized by the mid-21st century [57]. In RCP8.5, greenhouse gas emissions continue to rise with business as usual throughout the 21st century. In this study, 17 GCM models included in MACA were used to create ensemble climate data for the historic (1965–2004) period and for four approximate quarter-century periods of the 21st century: quarter 1, 2006–2025; quarter 2, 2026–2050; quarter 3, 2051–2075; and quarter 4, 2076–2099. Historical and future potential evapotranspiration (PET) were calculated for the region based on the Penman–Montieth method combined with the regional MACA dataset [16]. E was estimated using the annual water balance, $E = P - Q + \Delta S$, based on the USGS water year, where P is the long-term average annual precipitation, Q is the long-term average streamflow, and ΔS is watershed storage, which is assumed to approach zero over a long time period.

GCMs have known uncertainties and statistical biases that limit their direct use for hydrological assessments especially at short time scales, such as daily to weekly [58–60]. To tackle the issue of statistical biases, several correction techniques have been developed to adjust modelled variables to observations [61]. The MACA dataset has been developed using the data from CMIP 5 models and using a comprehensive six step downscaling and bias correcting approach and has been validated against observations [56]. The information from GCMs can also be informative if applied for long-term assessments [62]. Since our sensitivity analysis based on the Budyko model is a long-term water balance analysis, we considered the MACA dataset a viable tool to analyze possible change scenarios for the study catchments.

2.2. Quantifying Historical Streamflow Sensitivity to Climate

Streamflow sensitivity [35] is an elasticity-based method [63] based on the formulation of the Budyko equation [14] by Choudhury [64]. It includes the adjustable parameter, n, which accounts for non-climatic factors that influence E, such as slope, vegetation, geology, and soils using catchment-specific E variability [65]. The n value is calculated from the intersection of the AI (PET/P) and evaporative index (ET/P) and plotted in the Budyko space based on the specific catchment parameters. The Budyko analysis incorporates intrinsic limitations due to the simplistic design structure and few required datasets. However, the approach is useful because it uses available data, and the macro-climatological processes within the Budyko analysis has been shown to meet the requirements for the long-term water balance and climatologic processes [66,67].

$$E = \frac{E \times PET}{(P^n + PET^n)^{1/n}} \quad (1)$$

where E is long-term evapotranspiration, PET is long-term potential evapotranspiration, P is long-term precipitation, and n is a dimensionless parameter describing catchment properties that modify the partitioning of P into E and Q.

Table 1. Historical (1950–2004) water balance, Budyko, and streamflow sensitivity coefficients for selected USGS gaging stations and HCDN catchments in the central Appalachian Mountains region, US. P: precipitation; Q: streamflow; E: evapotranspiration; PET: potential evapotranspiration.

Basin/Station Name	Sensitivity Coefficients												
	ID	Station Number	Area	P	Q	E	PET	PET/P	E/P	n	$\Delta P/P$	$\Delta PET/PET$	$\Delta n/n$
			km ²	mm	mm	mm	mm	-	-	-	-	-	-
<i>Monongahela</i>													
Casselman River at Grantsville, MD	1M	3078000	163	1172	678	494	1228	1.05	0.42	0.78	1.36	−0.36	0.65
West Fork River at Enterprise, WV	2M	3061000	1965	1170	529	641	1310	1.12	0.55	1.06	1.57	−0.57	0.79
Youghiogheny River near Oakland, MD	3M	3075500	347	1275	824	451	1203	0.94	0.35	0.69	1.28	−0.28	0.55
Laurel Hill Creek at Ursina, PA	4M	3080000	313	1275	778	497	1203	0.94	0.39	0.76	1.33	−0.33	0.58
Cheat River near Parsons, WV	5M	3069500	1869	1329	870	459	1215	0.91	0.35	0.68	1.27	−0.27	0.54
Basin average			932	1244	736	508	1232	0.99	0.41	0.79	1.36	−0.36	0.62
<i>Ohio</i>													
Little Shenango River at Greenville, PA	1O	3102500	269	1012	490	522	1253	1.24	0.52	0.91	1.48	−0.48	0.81
Little Beaver Creek near East Liverpool, OH	2O	3109500	1284	1047	376	671	1316	1.26	0.64	1.26	1.76	−0.76	0.97
Basin average			777	1029	433	596	1285	1.25	0.58	1.08	1.62	−0.62	0.89
<i>Kanawha</i>													
Wolf Creek near Narrows, VA	1K	3175500	577	1002	481	520	1414	1.41	0.52	0.85	1.46	−0.46	0.87
Greenbrier River at Durbin, WV	2K	3180500	344	1246	719	527	1187	0.95	0.42	0.83	1.37	−0.37	0.61
Williams River at Dyer, WV	3K	3186500	331	1479	949	530	1224	0.83	0.36	0.75	1.30	−0.30	0.52
Big Coal River at Ashford, WV	4K	3198500	1012	1196	490	706	1376	1.15	0.59	1.17	1.66	−0.66	0.85
Bluestone River at Pipestem, WV	5K	3179000	1020	1018	423	595	1381	1.36	0.58	1.02	1.59	−0.59	0.94
Greenbrier River at Alderson, WV	6K	3183500	3531	1080	520	560	1304	1.21	0.52	0.93	1.49	−0.49	0.80
Basin average			1136	1170	597	573	1314	1.15	0.50	0.92	1.48	−0.48	0.76
<i>Tennessee</i>													
North Fork Holston River near Saltsville, VA	1T	3488000	572	1155	481	674	1435	1.24	0.58	1.08	1.62	−0.62	0.89
Clinch River above Tazewell, TN	2T	3528000	3816	1275	485	791	1433	1.12	0.62	1.30	1.75	−0.75	0.87
Little Tennessee River near Prentiss, NC	3T	3500000	362	1695	960	735	1443	0.85	0.43	0.92	1.41	−0.41	0.57
Basin average			1584	1375	642	733	1437	1.07	0.55	1.10	1.59	−0.59	0.78

Table 1. Cont.

Basin/Station Name	Sensitivity Coefficients												
	ID	Station Number	Area	P	Q	E	PET	PET/P	E/P	n	$\Delta P/P$	$\Delta PET/PET$	$\Delta n/n$
<i>Potomac</i>													
Wills Creek near Cumberland, MD	1P	1601500	639	988	494	494	1352	1.37	0.50	0.82	1.44	−0.44	0.83
Potomac River near at Paw Paw, WV	2P	1610000	8101	988	398	591	1352	1.37	0.60	1.05	1.62	−0.62	0.96
Cacapon River near Great Cacapon, WV	3P	1611500	1748	998	321	677	1387	1.39	0.68	1.29	1.84	−0.83	1.09
Patterson Creek near Headsville, WV	4P	1604500	572	1071	283	788	1303	1.22	0.74	1.75	2.16	−1.16	1.08
Bennett Creek at Park Mills, MD	5P	1634500	163	1040	399	641	1413	1.36	0.62	1.11	1.67	−0.67	0.98
South Branch Potomac River near Springfield, WV	6P	1608500	3783	973	347	626	1364	1.40	0.64	1.17	1.73	−0.73	1.04
Conococheague Creek and Fairview, MD	7P	1614500	1279	1004	452	552	1404	1.40	0.55	0.92	1.52	−0.52	0.90
Marsh Run at Grimes, MD	8P	1617800	49	1014	223	791	1427	1.41	0.78	1.76	2.26	−1.26	1.31
North Branch Potomac River at Steyer, MD	9P	1595000	189	941	322	619	1342	1.43	0.66	1.20	1.76	−0.76	1.08
Catoctin Creek near Middletown, MD	10P	1637500	173	1063	419	644	1424	1.34	0.61	1.09	1.65	−0.65	0.96
Goose Creek near Leesburg, VA	11P	1644000	860	1081	366	715	1441	1.33	0.66	1.27	1.80	−0.80	1.04
North Fork Shenandoah River at Cootes Store, VA	12P	1632000	544	995	348	647	1382	1.39	0.65	1.20	1.75	−0.75	1.05
Cedar Creek near Winchester, VA	13P	1643500	264	1040	366	674	1413	1.36	0.65	1.22	1.76	−0.76	1.03
Basin average			1413	1015	364	651	1385	1.37	0.64	1.22	1.76	−0.76	1.03
Regional average			1246	1125	510	615	1342	1.22	0.56	1.06	1.61	−0.61	0.87
±std. dev.			1671	167	198	98	82	0.19	0.11	0.26	0.23	0.23	0.20

Equation (1) can be used to quantify the change in E due to changes in climate (P, PET) and n [35]:

$$\Delta E = \frac{\partial E}{\partial P} \Delta P + \frac{\partial E}{\partial PET} \Delta PET + \frac{\partial E}{\partial n} \Delta n \quad (2)$$

The respective partial differentials are given by Equations (3a)–(3c), which provide insight into how changes in climate (P, PET) and land cover (n) affect E.

$$\frac{\partial E}{\partial P} = \frac{E}{P} \left(\frac{PET^n}{P^n + PET^n} \right) \quad (3a)$$

$$\frac{\partial E}{\partial PET} = \frac{E}{PET} \left(\frac{P^n}{P^n + PET^n} \right) \quad (3b)$$

$$\frac{\partial E}{\partial n} = \frac{E}{n} \left(\frac{\ln(P^n + PET^n)}{n} \right) - \frac{(P^n \ln P + PET^n \ln PET)}{P^n + PET^n} \quad (3c)$$

It is assumed that the water balance changes over time are from one steady state to another steady state [35]; i.e., that transient changes in storage can be ignored [67]. Based on this assumption, Q was calculated by

$$\Delta Q = \Delta P - \Delta E \quad (4)$$

By combining Equations (2) and (4), ΔQ is given by

$$\Delta Q = \left(1 - \frac{\partial E}{\partial P} \right) \Delta P - \frac{\partial E}{\partial PET} \Delta PET - \frac{\partial E}{\partial n} \Delta n \quad (5)$$

Relative ΔQ is then solved by

$$\frac{\Delta Q}{Q} = \left[\frac{P}{Q} \left(1 - \frac{\partial E}{\partial P} \right) \right] \frac{\Delta P}{P} - \left[\frac{PET}{Q} \frac{\partial E}{\partial PET} \right] \frac{\Delta PET}{PET} - \left[\frac{n}{Q} \frac{\partial E}{\partial n} \right] \frac{\Delta n}{n} \quad (6)$$

The terms in square brackets are the sensitivity coefficients expressing the effect of changing P and PET on relative ΔQ (Table 1), where $\Delta P/P$ represents the theoretical sensitivity of streamflow to changes in precipitation, $\Delta PET/PET$ represents the sensitivity of streamflow to changes in energy (PET), and $\Delta n/n$ represents the change in Q following a change in watershed characteristics. An increase in $\Delta P/P$ will increase Q, while an increase in $\Delta PET/PET$ and $\Delta n/n$ will decrease Q.

2.3. Modeling Future Streamflow

The sensitivity of future Q to future changes in P and PET was modeled using historical sensitivity coefficients and future climates based on ensemble RCP4.5 and RCP8.5 data. Future changes in P and PET were calculated relative to the historical period (H):

$$\frac{\Delta P}{P} RCP, x = \frac{P_{RCP, x} - P_H}{P_H} \quad (7)$$

$$\frac{\Delta PET}{PET} RCP, x = \frac{PET_{RCP, x} - PET_H}{PET_H} \quad (8)$$

Substituting future values of P and PET into Equation (5) with the historical sensitivity coefficients for P and PET (Equations (3a)–(3c)), future ΔQ was quantified by

$$\Delta Q = \left(1 - \frac{\Delta P}{P} \right) \Delta P_{RCP, x} - \frac{\Delta PET}{PET} \Delta PET_{RCP, x} - \frac{\Delta n}{n} \Delta n \quad (9)$$

Because our analysis focused on HCDN catchments, we assumed that catchment properties (parameter n) do not change in the future, thereby setting the n sensitivity coefficient and Δn to

0. We recognize that this assumption is likely an oversimplification of future landscape conditions, particularly in light of changes in forest structure, age, productivity, and growing season length [32,68,69] in relatively undisturbed catchments throughout the region. Future analysis should consider Δn to more thoroughly account for ecosystem changes important to the partition of P into E and Q .

3. Results

3.1. Historic Climate, Water Balance Components, and Streamflow Sensitivity throughout the Central Appalachian Mountains Region

Long-term average annual climate, water balance, and Budyko components over the historical period (1965–2004) are summarized in Table 1. Annual precipitation averaged 1125 ± 167 mm across the region. P was greatest in the Tennessee basin ($\bar{x} = 1375$ mm), followed by the Monongahela ($\bar{x} = 1244$ mm), Kanawha ($\bar{x} = 1170$ mm), Ohio ($\bar{x} = 1029$ mm), and the Potomac ($\bar{x} = 1015$ mm). Annual Q averaged 510 ± 198 mm across the region and was greatest in the Monongahela basin ($\bar{x} = 736$ mm), followed by the Tennessee ($\bar{x} = 642$ mm), Kanawha ($\bar{x} = 597$ mm), Ohio ($\bar{x} = 433$ mm) and the Potomac ($\bar{x} = 364$ mm). Annual E and PET averaged 615 ± 98 mm and 1342 ± 83 mm, respectively, generally following a south-to-north gradient. E was greatest in the Tennessee basin ($\bar{x} = 733$ mm), followed by the Potomac ($\bar{x} = 651$ mm), Ohio ($\bar{x} = 596$ mm), Kanawha ($\bar{x} = 573$ mm), and Monongahela ($\bar{x} = 508$ mm). PET averaged 1437 mm in the Tennessee, 1385 mm in the Potomac, 1314 mm in the Kanawha, 1285 mm in the Ohio, and 1232 mm in the Monongahela.

The aridity index, AI , averaged 1.22 ± 0.19 across the region, and was greatest in the Potomac ($\bar{x} = 1.37$) and smallest in the Monongahela basin ($\bar{x} = 0.99$) (Table 1). The evaporation ratio, E/P , which represents the proportion of P returned to the atmosphere through actual E , averaged 0.56 ± 0.11 across the region. Similar to AI , E/P was greatest in the Potomac ($\bar{x} = 0.64$) and smallest in the Monongahela basin ($\bar{x} = 0.41$) (Figure 2). The catchment-specific landscape parameter, n , averaged 1.61 ± 0.23 across the region, and was greatest in the Potomac ($\bar{x} = 1.76$) and smallest in the Monongahela basin ($\bar{x} = 0.79$) (Figure 3).

Streamflow sensitivity coefficients, which quantify the historical sensitivity of Q to changes in climate and catchment properties, averaged 1.61 ± 0.23 ($\Delta P/P$), 0.61 ± 0.23 ($\Delta PET/PET$), and 0.87 ± 0.20 ($\Delta n/n$) across the region (Table 1). These imply that Q is more sensitive to ΔP than ΔPET and Δn . Based on this, the theoretical results from Equation (6) predict that, for example, a 10% increase in P would increase Q by 16%, while a 10% increase in PET would decrease Q by 6%, and a 10% increase in landcover change would decrease Q by 8.7% [35] (Figure 4).

Figure 2. Historical (1965–2005) (A) aridity index (PET/P) and (B) evaporative index (E/P).

Figure 3. Landcover characteristics displayed as (A) the n value and (B) slope in degrees.

Figure 4. Sensitivity of streamflow to changes in (A) precipitation and (B) PET using data from 1965–2004.

3.2. Twenty-First Century Climate and Streamflow

Future climates (P, PET, AI) are summarized by RCP in Tables 2 and 3. For each pathway, P, PET, and AI at the catchment scale were projected to increase over the 21st century, albeit at different rates. Relative to the historic period, P was projected to increase in all catchments on average by 4% and 8% over the century for RCP4.5 and RCP8.5, respectively. Changes were greatest during the last quarter (2075–2099) of the 21st century, with P increasing between 1%–14% for RCP4.5 and 5%–15% for RCP8.5. PET is projected to progressively increase throughout the 21st century by 10% and 15%, on average, for RCP4.5 and RCP8.5, respectively.

Similar to P, the greatest changes in PET were in Quarter 4, increasing between 11%–17% for RCP4.5 and 5%–15% for RCP8.5. Changes in AI largely follow patterns in P and PET, increasing on average by 4% for RCP4.5 and 9% for RCP8.5 throughout the region. By the end of the century, AI was projected to be greatest over the study period, with changes ranging between 0.2%–11% (RCP4.5) and 8%–22% (RCP8.5).

Future Q are summarized in Table 4 and Figures 5 and 6. Q is projected to increase across catchments, basins, and the region under RCP4.5, with 93%–100% of catchments experiencing positive changes over the century. Changes across catchments were generally similar in magnitude when averaged across basins and ranged between 9% to 13% and. Under RCP8.5, Q was projected to be more variable in the future, decreasing by as much as 9% and increasing by as much as 9% (Table 4). Q increased early (2005–2025) in the century, with 28/29 catchments experiencing greater Q relative to the historic period. Q progressively decreased throughout the century, with nearly half of the catchments experiencing decreases in Q by mid- and late-century periods.

Table 2. Future (2005–2099) long-term annual precipitation (P), potential evapotranspiration (PET), and aridity index (AI) and changes by quarter for RCP4.5 for selected HCDN catchments.

RCP4.5		Q1 (2005–2025)						Q2 (2026–2050)						Q3 (2051–2075)						Q4 (2076–2099)					
Basin/Station Name	P	DP	PET	DPET	AI	DAI	P	DP	PET	DPET	AI	DAI	P	DP	PET	DPET	AI	DAI	P	DP	PET	DPET	AI	DAI	
	mm	%	mm	%	-	%	mm	%	mm	%	-	%	mm	%	mm	%	-	%	mm	%	mm	%	-	%	
Monongahela																									
Casselman River at Grantsville, MD	1217	4	1302	6	1.07	2	1230	5	1349	10	1.10	5	1245	6	1389	13	1.12	7	1266	8	1396	14	1.10	5	
West Fork River at Enterprise, WV	1212	4	1385	6	1.14	2	1228	5	1430	9	1.16	4	1247	7	1467	12	1.18	5	1260	8	1475	13	1.17	5	
Youghiogheny River near Oakland, MD	1324	4	1275	6	0.96	2	1340	5	1321	10	0.99	5	1359	7	1359	13	1.00	6	1374	8	1367	14	0.99	5	
Laurel Hill Creek at Ursina, PA	1298	2	1318	10	1.02	8	1313	3	1364	13	1.04	10	1331	4	1402	17	1.05	12	1347	6	1410	17	1.05	11	
Cheat River near Parsons, WV	1379	4	1288	6	0.93	2	1394	5	1336	10	0.96	5	1418	7	1372	13	0.97	6	1430	8	1381	14	0.97	6	
Basin average	1286	3	1314	7	1.03	3	1301	5	1360	10	1.05	6	1320	6	1398	14	1.06	7	1335	7	1406	14	1.06	6	
Ohio																									
Little Shenango River at Greenville, PA	1058	4	1328	6	1.26	1	1066	5	1372	10	1.29	4	1084	7	1412	13	1.30	5	1090	8	1421	13	1.30	5	
Little Beaver Creek near East Liverpool, OH	1084	4	1394	6	1.29	2	1099	5	1438	9	1.31	4	1116	7	1476	12	1.32	5	1123	7	1485	13	1.32	5	
Basin average	1071	4	1361	6	1.27	2	1083	5	1405	9	1.30	4	1100	7	1444	12	1.31	5	1106	7	1453	13	1.31	5	
Kanawha																									
Wolf Creek near Narrows, VA	1040	4	1486	5	1.43	1	1047	4	1537	9	1.47	4	1063	6	1570	11	1.48	5	1076	7	1579	12	1.47	4	
Greenbrier River at Durbin, WV	1298	4	1259	6	0.97	2	1316	6	1309	10	0.99	4	1331	7	1345	13	1.01	6	1349	8	1354	14	1.00	5	
Williams River at Dyer, WV	1533	4	1293	6	0.84	2	1548	5	1341	10	0.87	5	1569	6	1376	12	0.88	6	1586	7	1385	13	0.87	6	
Big Coal River at Ashford, WV	1235	3	1451	5	1.18	2	1242	4	1500	9	1.21	5	1261	5	1531	11	1.21	6	1274	7	1543	12	1.21	5	
Bluestone River at Pipestem, WV	1058	4	1453	5	1.37	1	1062	4	1504	9	1.42	4	1079	6	1537	11	1.42	5	1090	7	1547	12	1.42	5	
Greenbrier River at Alderson, WV	1123	4	1373	5	1.22	1	1127	4	1422	9	1.26	5	1143	6	1455	12	1.27	6	1157	7	1465	12	1.27	5	
Basin average	1214	4	1386	5	1.17	2	1223	5	1436	9	1.20	5	1241	6	1469	12	1.21	5	1255	7	1479	13	1.21	5	

Table 2. Cont.

RCP4.5	Q1 (2005–2025)						Q2 (2026–2050)						Q3 (2051–2075)						Q4 (2076–2099)					
Basin/Station Name	P	DP	PET	DPET	AI	DAI	P	DP	PET	DPET	AI	DAI	P	DP	PET	DPET	AI	DAI	P	DP	PET	DPET	AI	DAI
<i>Tennessee</i>																								
North Fork Holston River near Saltsville, VA	1195	3	1516	6	1.27	2	1196	4	1569	9	1.31	6	1222	6	1597	11	1.31	5	1236	7	1608	12	1.30	5
Clinch River above Tazewell, TN	1319	3	1503	5	1.14	1	1309	3	1556	9	1.19	6	1342	5	1582	10	1.18	5	1354	6	1595	11	1.18	5
Little Tennessee River near Prentiss, NC	1753	3	1512	5	0.86	1	1745	3	1567	9	0.90	6	1793	6	1599	11	0.89	5	1819	7	1612	12	0.89	4
Basin average	1422	3	1510	5	1.09	2	1417	3	1564	9	1.13	6	1452	6	1593	11	1.13	5	1469	7	1605	12	1.12	5
<i>Potomac</i>																								
Wills Creek near Cumberland, MD	1025	4	1429	6	1.39	2	1038	5	1475	9	1.42	4	1048	6	1515	12	1.44	6	1070	8	1522	13	1.42	4
Potomac River near at Paw Paw, WV	994	1	1436	6	1.44	6	1005	2	1482	10	1.47	8	1017	3	1522	13	1.50	9	1037	5	1529	13	1.47	8
Cacapon River near Great Cacapon, WV	1040	4	1465	6	1.41	1	1049	5	1510	9	1.44	4	1062	6	1550	12	1.46	5	1084	9	1558	12	1.44	3
Patterson Creek near Headsville, WV	1112	4	1379	6	1.24	2	1126	5	1426	9	1.27	4	1139	6	1466	12	1.29	6	1156	8	1473	13	1.27	5
Bennett Creek at Park Mills, MD	1084	4	1489	5	1.37	1	1098	6	1538	9	1.40	3	1110	7	1576	12	1.42	5	1135	9	1584	12	1.40	3
South Branch Potoamc River near Springfield, WV	1013	4	1441	6	1.42	2	1025	5	1488	9	1.45	4	1036	7	1529	12	1.47	5	1057	9	1536	13	1.45	4
Conococheague Creek and Fairview, MD	1046	4	1481	5	1.42	1	1057	5	1527	9	1.45	3	1070	7	1567	12	1.46	5	1092	9	1575	12	1.44	3
Marsh Run at Grimes, MD	1059	4	1505	5	1.42	1	1066	5	1551	9	1.46	4	1080	6	1592	12	1.47	5	1104	9	1599	12	1.45	3
North Branch Potomac River at Steyer, MD	980	4	1419	6	1.45	2	992	5	1466	9	1.48	4	1003	7	1505	12	1.50	5	1019	8	1513	13	1.48	4
Catoctin Creek near Middletown, MD	1109	4	1501	5	1.35	1	1115	5	1548	9	1.39	4	1130	6	1589	12	1.41	5	1158	9	1597	12	1.38	3
Goose Creek near Leesburg, VA	1129	4	1518	5	1.34	1	1136	5	1566	9	1.38	3	1153	7	1606	11	1.39	5	1179	9	1614	12	1.37	3
North Fork Shenandoah River at Cootes Store, VS	1037	4	1458	6	1.41	1	1052	6	1509	9	1.43	3	1064	7	1548	12	1.45	5	1085	9	1556	13	1.44	3
Cedar Creek near Winchester, VA	1136	9	1513	7	1.33	-2	1137	9	1560	10	1.37	1	1155	11	1600	13	1.39	2	1181	14	1609	14	1.36	0.2
Basin average	1059	4	1464	6	1.38	1.40	1069	5	1511	9	1.42	4	1082	7	1551	12	1.44	5	1104	9	1559	13	1.41	4
Regional average	1169	4	1420	6	1	2	1178	5	1468	9	1	4	1196	6	1505	12	1	6	1213	8	1513	13	1	5
±std. dev	171	1.3	82	0.8	0.2	1.5	169	1.3	83	0.9	0.2	1.6	175	1.2	82	1.1	0.2	1.6	175	1.5	83	1.1	0.2	1.8

Table 3. Future (2005–2099) long-term annual precipitation (P), potential evapotranspiration (PET), and aridity index (AI) and changes by quarter for RCP8.5 for selected HCDN catchments.

RCP8.5		Q1 (2005–2025)						Q2 (2026–2050)						Q3 (2051–2075)						Q4 (2076–2099)					
Basin/Station Name		P	DP	PET	DPET	AI	DAI	P	DP	PET	DPET	AI	DAI	P	DP	PET	DPET	AI	DAI	P	DP	PET	DPET	AI	DAI
		mm	%	mm	%	-	%	mm	%	mm	%	-	%	mm	%	mm	%	-	%	mm	%	mm	%	-	%
<i>Monongahela</i>																									
Casselman River at Grantsville, MD		1223	4	1322	8	1.08	3	1227	5	1375	12	1.12	7	1248	6	1471	20	1.18	12	1276	9	1547	26	1.21	15
West Fork River at Enterprise, WV		1223	5	1406	7	1.15	4	1223	5	1456	11	1.19	7	1241	6	1549	18	1.25	12	1272	9	1621	24	1.27	15
Youghiogheny River near Oakland, MD		1328	4	1295	8	0.97	4	1334	5	1345	12	1.01	7	1355	6	1437	20	1.06	13	1385	9	1510	26	1.09	16
Laurel Hill Creek at Ursina, PA		1308	3	1339	11	1.02	9	1309	3	1390	16	1.06	13	1327	4	1484	23	1.12	19	1358	7	1558	30	1.15	22
Cheat River near Parsons, WV		1386	4	1310	8	0.95	4	1390	5	1361	12	0.98	8	1409	6	1455	20	1.03	13	1438	8	1529	26	1.06	17
Basin average		1294	4	1334	8	1.03	5	1297	4	1385	13	1.07	8	1316	6	1479	20	1.13	14	1346	8	1553	26	1.16	17
<i>Ohio</i>																									
Little Shenango River at Greenville, PA		1069	6	1346	7	1.26	2	1066	5	1399	12	1.31	6	1074	6	1495	19	1.39	13	1115	10	1571	25	1.41	14
Little Beaver Creek near East Liverpool, OH		1096	5	1413	7	1.29	2	1097	5	1465	11	1.34	6	1106	6	1561	19	1.41	12	1141	9	1635	24	1.43	14
Basin average		1083	5	1379	7	1.27	2	1082	5	1432	11	1.32	6	1090	6	1528	19	1.40	12	1128	10	1603	25	1.42	14
<i>Kanawha</i>																									
Wolf Creek near Narrows, VA		1034	3	1507	7	1.46	3	1049	5	1558	10	1.49	5	1066	6	1646	16	1.54	9	1080	8	1725	22	1.60	13
Greenbrier River at Durbin, WV		1294	4	1280	8	0.99	4	1308	5	1332	12	1.02	7	1334	7	1424	20	1.07	12	1353	9	1500	26	1.11	16
Williams River at Dyer, WV		1536	4	1314	7	0.86	3	1541	4	1364	11	0.89	7	1561	6	1454	19	0.93	13	1586	7	1527	25	0.96	16
Big Coal River at Ashford, WV		1232	3	1477	7	1.20	4	1235	3	1525	11	1.23	7	1249	4	1616	17	1.29	13	1272	6	1690	23	1.33	16
Bluestone River at Pipestem, WV		1053	3	1476	7	1.40	3	1067	5	1526	11	1.43	6	1076	6	1619	17	1.50	11	1092	7	1699	23	1.56	15
Greenbrier River at Alderson, WV		1117	3	1395	7	1.25	4	1130	5	1444	11	1.28	6	1144	6	1531	17	1.34	11	1160	7	1605	23	1.38	15
Basin average		1211	3	1408	7	1.19	4	1222	4	1458	11	1.22	6	1238	6	1548	18	1.28	11	1257	7	1624	24	1.32	15
<i>Tennessee</i>																									
North Fork Holston River near Saltsville, VA		1194	3	1539	7	1.29	4	1202	4	1588	11	1.32	6	1211	5	1676	17	1.38	11	1226	6	1753	22	1.43	15
Clinch River above Tazewell, TN		1318	3	1528	7	1.16	3	1316	3	1576	10	1.20	6	1322	4	1659	16	1.26	12	1343	5	1726	20	1.29	14
Little Tennessee River near Prentiss, NC		1766	4	1533	6	0.87	2	1765	4	1586	10	0.90	6	1780	5	1675	16	0.94	11	1780	5	1753	22	0.98	16
Basin average		1426	4	1533	7	1.11	3	1428	4	1583	10	1.14	6	1437	5	1670	16	1.19	11	1449	5	1744	21	1.23	15
<i>Potomac</i>																									
Wills Creek near Cumberland, MD		1032	4	1449	7	1.40	3	1037	5	1501	11	1.45	6	1056	7	1595	18	1.51	10	1080	9	1669	23	1.55	13
Potomac River near Great Cacapon, WV		999	1	1455	8	1.46	6	1005	2	1508	12	1.50	10	1023	4	1601	18	1.56	14	1046	6	1675	24	1.60	17
Cacapon River near Great Cacapon, WV		1044	5	1483	7	1.42	2	1050	5	1537	11	1.46	5	1069	7	1629	17	1.52	10	1096	10	1703	23	1.55	12
Patterson Creek near Headsville, WV		1116	4	1399	7	1.25	3	1122	5	1452	11	1.29	6	1143	7	1547	19	1.35	11	1168	9	1621	24	1.39	14
Bennett Creek at Park Mills, MD		1078	4	1509	7	1.40	3	1095	5	1564	11	1.43	5	1123	8	1656	17	1.47	9	1143	10	1733	23	1.52	12
South Branch Potoamc River near Springfield, WV		1017	4	1460	7	1.44	2	1024	5	1515	11	1.48	6	1043	7	1609	18	1.54	10	1066	10	1685	24	1.58	13
Conococheague Creek and Fairview, MD		1049	4	1500	7	1.43	2	1058	5	1554	11	1.47	5	1078	7	1647	17	1.53	9	1105	10	1722	23	1.56	12
Marsh Run at Grimes, MD		1061	5	1524	7	1.44	2	1068	5	1579	11	1.48	5	1088	7	1673	17	1.54	9	1119	10	1748	22	1.56	11
North Branch Potomac River at Steyer, MD		981	4	1439	7	1.47	3	989	5	1492	11	1.51	6	1009	7	1586	18	1.57	10	1030	9	1661	24	1.61	13
Catocin Creek near Middletown, MD		1109	4	1521	7	1.37	2	1119	5	1577	11	1.41	5	1140	7	1669	17	1.46	9	1172	10	1745	23	1.49	11
Goose Creek near Leesburg, VA		1126	4	1538	7	1.37	2	1138	5	1594	11	1.40	5	1164	8	1686	17	1.45	9	1191	10	1763	22	1.48	11
North Fork Shenandoah River at Cootes Store, VS		1032	4	1480	7	1.43	3	1048	5	1536	11	1.47	6	1074	8	1631	18	1.52	9	1093	10	1710	24	1.56	13
Cedar Creek near Winchester, VA		1131	9	1532	8	1.35	0	1141	10	1589	12	1.39	2	1163	12	1680	19	1.44	6	1198	15	1755	24	1.46	8
Basin average		1060	4	1484	7	1.40	3	1069	5	1538	11	1.44	6	1090	7	1632	18	1.50	10	1116	10	1707	23	1.53	12
Regional average		1174	4	1441	7	1.25	3.2	1180	5	1493	11	1.29	6	1198	6	1585	18	1.35	11	1222	8	1659	24	1.38	14
±std. dev.		167	1	83	1	0.18	1.5	165	1	84	1	0.19	2	165	2	83	2	0.19	2	162	2	83	2	0.19	3

Table 4. Future (2005–2099) changes in long-term annual streamflow (ΔQ) due to changes in precipitation (ΔQ_P) and potential evapotranspiration (ΔQ_{PET}) relative to the historical period (1950–2004) based on RCP4.5 and RCP8.5.

Basin /Station Name	Q1 (2005–2025)			Q2 (2026–2050)			Q3 (2051–2075)			Q4 (2076–2099)			Q1 (2005–2025)			Q2 (2026–2050)			Q3 (2051–2075)			Q4 (2076–2099)		
	DQ _P %	D Q _{PET} %	DQ %	DQ _P %	D Q _{PET} %	DQ %	DQ _P %	D Q _{PET} %	DQ %	DQ _P %	D Q _{PET} %	DQ %	DQ _P %	D Q _{PET} %	DQ %	DQ _P %	D Q _{PET} %	DQ %	DQ _P %	D Q _{PET} %	DQ %	DQ _P %	D Q _{PET} %	DQ %
<i>Monongahela</i>																								
Casselman River at Grantsville, MD	5	−2	3	7	−4	3	8	−5	4	11	−5	6	6	−3	3	6	−4	2	9	−7	2	12	−9	3
West Fork River at Enterprise, WV	6	−3	2	8	−5	3	10	−7	4	12	−7	5	7	−4	3	7	−6	1	10	−10	−1	14	−14	0
Youghiogheny River near Oakland, MD	5	−2	3	7	−3	4	8	−4	5	10	−4	6	5	−2	3	6	−3	3	8	−5	3	11	−7	4
Laurel Hill Creek at Ursina, PA	2	−3	−1	4	−4	0	6	−5	0	7	−6	2	3	−4	0	4	−5	−2	5	−8	−2	9	−10	−1
Cheat River near Parsons, WV	5	−2	3	6	−3	4	9	−4	5	10	−4	6	5	−2	3	6	−3	3	8	−5	2	10	−7	3
Basin average	5	−2	2	6	−4	3	8	−5	3	10	−5	5	5	−3	2	6	−5	1	8	−7	1	11	−9	2
<i>Ohio</i>																								
Little Shenango River at Greenville, PA	7	−3	4	8	−5	3	11	−6	4	11	−6	5	8	−4	5	8	−6	2	9	−9	0	15	−12	3
Little Beaver Creek near East Liverpool, OH	6	−5	2	9	−7	2	12	−9	2	13	−10	3	8	−6	3	9	−9	0	10	−14	−4	16	−19	−3
Basin average	6	−4	3	8	−6	3	11	−8	3	12	−8	4	8	−5	4	8	−7	1	9	−12	−2	16	−15	0
<i>Kanawha</i>																								
Wolf Creek near Narrows, VA	6	−2	3	7	−4	3	9	−5	4	11	−5	5	5	−3	2	7	−5	2	9	−8	2	11	−10	1
Greenbrier River at Durbin, WV	6	−2	3	8	−4	4	9	−5	4	11	−5	6	5	−3	2	7	−5	2	10	−7	2	12	−10	2
Williams River at Dyer, WV	5	−2	3	6	−3	3	8	−4	4	9	−4	5	5	−2	3	5	−3	2	7	−6	2	9	−7	2
Big Coal River at Ashford, WV	5	−4	2	6	−6	0	9	−7	2	11	−8	3	5	−5	0	5	−7	−2	7	−12	−4	11	−15	−5
Bluestone River at Pipestem, WV	6	−3	3	7	−5	2	9	−7	3	11	−7	4	5	−4	1	8	−6	1	9	−10	−1	12	−14	−2
Greenbrier River at Alderson, WV	6	−3	3	6	−4	2	9	−6	3	11	−6	4	5	−3	2	7	−5	2	9	−9	0	11	−11	0
Basin average	6	−3	3	7	−4	2	9	−6	3	11	−6	5	5	−3	2	6	−5	1	9	−9	0	11	−11	0

Table 4. Cont.

Basin /Station Name	Q1 (2005–2025)			Q2 (2026–2050)			Q3 (2051–2075)			Q4 (2076–2099)			Q1 (2005–2025)			Q2 (2026–2050)			Q3 (2051–2075)			Q4 (2076–2099)		
	DQ _P	D	DQ	DQ _P	D	DQ	DQ _P	D	DQ	DQ _P	D	DQ	DQ _P	D	DQ	DQ _P	D	DQ	DQ _P	D	DQ	DQ _P	D	DQ
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
<i>Tennessee</i>																								
North Fork Holston River near Saltsville, VA	6	−3	2	6	−6	0	9	−7	2	11	−7	4	6	−4	1	7	−7	0	8	−10	−3	10	−14	−4
Clinch River above Tazewell, TN	6	−4	2	5	−6	−2	9	−8	1	11	−9	2	6	−5	1	6	−7	−2	6	−12	−5	9	−15	−6
Little Tennessee River near Prentiss, NC	5	−2	3	4	−4	1	8	−4	4	10	−5	5	6	−3	3	6	−4	2	7	−7	0	7	−9	−2
Basin average	6	−3	2	5	−5	0	9	−6	2	11	−7	4	6	−4	2	6	−6	0	7	−10	−2	9	−13	−4
<i>Potomac</i>																								
Wills Creek near Cumberland, MD	5	−2	3	7	−4	3	9	−5	3	12	−5	6	6	−3	3	7	−5	2	10	−8	2	13	−10	3
Potomac River near at Paw Paw, WV	1	−4	−3	3	−6	−3	5	−8	−3	8	−8	0	2	−5	−3	3	−7	−4	6	−11	−6	10	−15	−5
Cacapon River near Great Cacapon, WV	8	−5	3	9	−7	2	12	−10	2	16	−10	6	9	−6	3	10	−9	1	13	−15	−1	18	−19	−1
Patterson Creek near Headsville, WV	8	−7	2	11	−11	0	14	−14	−1	17	−15	2	9	−8	1	10	−13	−3	15	−22	−7	20	−28	−9
Bennett Creek at Park Mills, MD	7	−4	3	9	−6	3	11	−8	4	15	−8	7	6	−5	2	9	−7	2	13	−12	2	16	−15	1
South Branch Potoamc River near Springfield, WV	7	−4	3	9	−7	3	11	−9	3	15	−9	6	8	−5	3	9	−8	1	12	−13	−1	17	−17	−1
Conococheague Creek and Fairview, MD	6	−3	3	8	−5	3	10	−6	4	13	−6	7	7	−4	3	8	−6	2	11	−9	2	15	−12	3
Marsh Run at Grimes, MD	10	−7	3	11	−11	0	15	−15	0	20	−15	5	10	−9	2	12	−13	−1	16	−22	−5	23	−28	−5
North Branch Potomac River at Steyer, MD	7	−4	3	9	−7	2	12	−9	2	15	−10	5	7	−5	2	9	−8	0	13	−14	−1	17	−18	−1
Catoctin Creek near Middletown, MD	7	−4	4	8	−6	2	10	−8	3	15	−8	7	7	−4	3	9	−7	2	12	−11	1	17	−15	2
Goose Creek near Leesburg, VA	8	−4	4	9	−7	2	12	−9	3	16	−10	7	8	−5	2	9	−9	1	14	−14	0	18	−18	0
North Fork Shenandoah River at Cootes Store, VS	7	−4	3	10	−7	3	12	−9	3	16	−9	6	6	−5	1	9	−8	1	14	−13	0	17	−18	−1
Cedar Creek near Winchester, VA	16	−5	11	16	−8	9	19	−10	9	24	−11	13	15	−6	9	17	−9	8	21	−14	6	27	−18	8
Basin average	8	−4	3	9	−7	2	12	−9	2	15	−10	6	8	−5	2	9	−8	1	13	−14	−1	17	−18	0
Regional average	6	−3	3	8	−6	2	10	−7	3	13	−8	5	7	−4	2	8	−7	1	10	−11	−1	14	−14	0
±std. dev	3	1	4	3	2	5	3	3	5	4	3	6	2	2	4	3	3	5	3	4	7	4	5	10

Figure 5. Changes in future streamflow for four future time periods based on RCP4.5 relative to the historic period (1950–2004). (A) 2005–2025; (B) 2026–2050; (C) 2051–2075; (D) 2076–2099.

Figure 6. Changes in future streamflow for four future time periods based on RCP8.5 relative to the historic period (1950–2004). (A) 2005–2025; (B) 2026–2050; (C) 2051–2075; (D) 2076–2099.

Streamflow changes attributed to changes in P (ΔQ_P) were greater than changes attributed to PET (ΔQ_{PET}) under RCP4.5 (Figure 5), but ΔQ_{PET} increased to comparable magnitudes of ΔQ_P late in the century under RCP8.5 (Table 4 and Figure 6). ΔQ_P increased by 1%–24% under RCP4.5 and 2%–27% under RCP8.5, while ΔQ_{PET} increased by 2%–15% and 2%–28% for RCPs 4.5 and 8.5, respectively (Figure 7).

Figure 7. Box plots of future (2005–2099) changes in long-term annual streamflow (ΔQ) attributed to changes in precipitation (ΔQ_P) and potential evapotranspiration (ΔQ_{PET}) for RCP4.5 and RCP8.5. Streamflow changes are relative to the historical period (1950–2004).

4. Discussion

4.1. Historic Climate, Water Balance Components, and Streamflow Sensitivity

The catchment-scale Q sensitivity to P was greater than 1 and generally increased with increasing E/P, while the sensitivity of Q to PET was negative and the absolute value generally increased with increasing E/P (Figures 2 and 4). This implies that sensitivity to climate conditions was greater in arid catchments (those in the Potomac basin) than humid catchments (those in the Monongahela basin), which is consistent with other energy-limited regions [70,71]. The sensitivity to both P and PET increases with increasing n value since the higher value of n generally corresponds to greater E for a given P and PET (Figure 2). The n value is a function of precipitation, topography, and slope [47,65,72,73], indicating lower water availability in regions with higher n value.

The catchment sensitivities to both P and PET generally follow the continental divide of the Appalachian Mountains, which occurs between the Monongahela and Potomac where runoff moves to the Chesapeake Bay, due to rainfall partitioning properties occurring in the headwater region (Figures 3 and 4). Catchments situated closer to the divide (Monongahela, Kanawha, eastern Tennessee) tend to have lower sensitivity, except for the northern catchment in Ohio (10), likely due to its proximity to the Great Lakes and therefore its lower PET. On the other hand, catchments east (leeward) of the divide tend to have greater sensitivity due to orographic lift, rainfall partitioning, and higher PET. Furthermore, high-elevation headwater catchments in the Monongahela, eastern Kanawha, and eastern Tennessee have lower sensitivity to P due to the low PET attributed to decreased temperatures and therefore lower aridity at high altitudes, which is consistent with other research conducted in the

Appalachian Mountains [16]. Sensitivity to both P and PET increases with decreasing latitude, as PET rises due to increased dependence on sunshine hours and therefore radiation and temperature.

While P, soil storage, and slope are important factors contributing to rainfall partitioning and Q sensitivity [65], landcover has important implications for rainfall partitioning in the region. Forests of the eastern US are highly dynamic [68,74] due to natural (e.g., chestnut blight) and anthropogenic (e.g., forest succession, harvesting, industrialization) drivers. Furthermore, forests of the region are changing due to the rapid increase in unconventional gas development and legacy of surface coal mining throughout the region [75–77], which will likely increase regional streamflow ($\Delta n/n$ in Table 1).

Forest disturbances due to harvesting [78,79], coal mining [76,80], urbanization [81], unconventional gas development, and afforestation [74] alter the amount of P partitioned into Q. Deforestation generally increases Q over the short-term by decreasing canopy interception and E [82], although the response of Q to forest removal also depends on the amount of water stored in a catchment [83]. As forests regrow, Q can return to similar pre-disturbance levels [84], but because tree water use and canopy interception differ among species (e.g., [85,86]), post-disturbance forest composition can alter Q over the long-term [53,87]. In the case of the forested catchments examined in this study, increases in deforestation will decrease n and E and increase Q (Table 1), while afforestation would show inverse relationships. Furthermore, forest disturbances over the 20th century have shifted the forest composition of the region from dominance by shade-intolerant and fire-adapted xerophytic species, which have adapted to live in areas with little water and low direct solar radiation (e.g., oaks (*Quercus*), chestnut (*Castanea*)), to shade-tolerant and fire-intolerant mesophytic species, which have adapted to variations in water content and high direct solar radiation (e.g., maple (*Acer*), cherry (*Prunus*)) [88]. Tree water use is generally higher for these species [85], which increases E and decreases Q [89]. Furthermore, the tree water use and carbon dynamics of these species are also more sensitive to variations in climate [86,90], and the sensitivity of Q to climate change can increase with the increasing density of mesophytic species [87]. Changes in forest age, productivity, and succession [91], as well as changes in growing season length [26,30,32], are important factors for water balance partitioning. Therefore, increases in mesophication, forest productivity, and growing season length will increase n and E and subsequently decrease Q.

4.2. Twenty-First Century Climate and Streamflow

Future climate changes projected for catchments in the central Appalachian Mountains region are consistent with other studies that show increases in both P and atmospheric water demand (e.g., [42,92,93]). Changes were greater in magnitude and variability with the more severe RCP compared to the more conservative pathway with lower atmospheric CO₂ equivalents [21,23,24]. Early in the 21st century, relative changes in P and PET were similar in magnitude, but by the century's end under RCP8.5, increases in PET were projected to outpace P increases in all catchments. The larger increases in PET move the heavily forested catchments of the region towards greater aridity [16], potentially jeopardizing their role as reliable sources of freshwater to downstream communities [2,89]. The projection of P and PET represents some level of uncertainty due to the physics and resolution of the downscaled model. PET exhibits greater uncertainty than P for the region, which is likely due to its greater dependency on temperature and solar radiation [15]. Uncertainty increases in lower portions of the regions and in Q3 for RCP4.5 and Q4 for RCP8.5 due to the degree of change that occurs during these time periods [16].

Under RCP4.5, ΔQ_P values were consistently greater than ΔQ_{PET} , with the net effect of increasing Q in 27 of 29 catchments for each future quarter period (Figure 5). Under RCP8.5, however, Q was more variable, decreasing by as much as 9% in quarter 4 for Patterson Creek and increasing by as much as 9% in the first quarter for Cedar Creek (both are located in the Potomac basin) (Figure 6). Across the region, Q was projected to increase in 28 of 29 catchments early in the century, but by the century's end, Q was projected to decrease in more than half of the catchments, moving closer to the historic long-term regional average. In this case, the disproportionately large increases in PET offset

potentially larger increases in Q due to ΔP [43] (Figures 5 and 6). An important caveat of our work was that we assumed no changes in catchment properties in the future ($\Delta n = 0$, Equation (9)); i.e., a transition from one steady state to another [35]. While quantifying future land use change and its role on Q sensitivity was beyond the scope of this paper, it is important for managers and decision makers to consider disturbance and climate change together.

While our analysis suggests relatively moderate Q changes throughout the 21st century at the long-term annual scale, other studies show greater variability across the hydrologic regime. The largest increases in P and Q are projected to occur during winter and early spring [39,41,43], when atmospheric demand and forest water use are low [16], increasing the frequency of flooding [23]. P , on the other hand, is projected to decrease during summer when PET and human and ecosystem water use are high, which decreases summer flow [39]. Throughout the greater mid-Atlantic region that includes our study catchments, peak flow events with a 1% exceedance probability are projected to increase by between 10%–20%, while low flows are projected to increase by as much as 14% [37,38,40].

5. Conclusions

Three clear patterns arise from our analysis on streamflow sensitivity to the changing climate in the central Appalachian region of the United States.

1. Catchments are more sensitive to P than PET throughout the region and increased with increasing E/P , implying that arid catchments were more sensitive to change. Sensitivity also increased with increasing distance from the continental divide, with catchments on the leeward (eastern) side of the divide more sensitive to change. Furthermore, sensitivity increased with decreasing elevation and decreasing latitude due to greater dependence on temperature and radiation in those catchments.

2. Future P and PET were greater in magnitude and variability with the more severe RCP (8.5). Early in the 21st century (2005–2025), changes in P and PET will remain consistent with each other; however, by 2099 under RCP 8.5, PET increases will outpace changes in P , which implies that business as usual CO_2 emissions could trigger increased aridity in the region and threaten water resource sustainability.

3. Under RCP4.5, future Q will increase in 27 of the 29 catchments for each future quarter period. However, under RCP 8.5, Q was more variable, especially in the catchments with high sensitivity in the Potomac basin. In the first half of the century (2005–2050), Q is projected to increase in 28/29 catchments, but by 2099, Q is projected to decrease in more than half of the catchments.

Our study contributes to the growing body of recent research that shows that anthropogenic climate change is altering freshwater provisioning throughout the region, posing considerable challenges for water resources management and water security. Floods, droughts, and low flow directly impact society through their immediate effects (e.g., pollution, inundation) and indirectly through ecosystem degradation, human health, work productivity, and the disruption of supply chains and the economy. Flooding poses significant risks to water quality and infrastructure. Increases in climate-driven droughts and low flows, due to the lack of precipitation or increase in atmospheric demand, degrades water quality and aquatic habitats by concentrating pollutants, increasing the costs of water treatment. As with much of the US, the central Appalachian region's roads, bridges, culverts, dams, and water treatment facilities are outdated, poorly maintained, and at a high risk of failure. Future changes in climate and streamflow will only increase the costs and damages to critical infrastructure. The changes in climate and hydrology found in this study suggest considerable challenges for managing the region's water quality, quantity, and security over the 21st century.

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