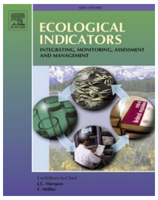
Ecological Indicators 121 (2021) 107194

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Short Note

Exploring relationships among stream health, human well-being, and demographics in Virginia, USA

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ARTICLE INFO

Keywords:
Ecosystem health
Environmental inequity
Public health
Social-ecological system

ABSTRACT

Quantification of empirical relationships between ecosystem health and human well-being is uncommon at broad spatial scales. We used public data for Virginia (USA) counties to examine pairwise correlations among two indicators of stream health, thirteen indicators of human well-being, and four demographic metrics. Our indicators of stream health included the Virginia Stream Condition Index (VSCI) and the percentage of stream kilometers with a fish consumption advisory (%FCA); these measures are inversely related. VSCI and %FCA were correlated with some indicators of human health, safety and security, and living standards, as well as with some demographic metrics. VSCI was most strongly correlated (positively) with the percentage of a county's population self-identifying as White; %FCA was most strongly correlated (positively) with overall mortality rate (number of deaths per 100,000 people). This exploratory study highlights the need for future multidisciplinary, multiscale studies to characterize toxicological, epidemiological, socioeconomic, and political linkages – including causal mechanisms – between ecosystem health and human well-being.

1. Introduction

Relationships between human well-being (HWB) and ecosystem health (EH) are widely presumed though quantification is limited (Millennium Ecosystem Assessment, 2005). The assumption that intact ecosystems benefit public health commonly justifies biodiversity conservation and environmental protection, especially in the context of managing water quality (Keeler et al., 2012; Sandifer et al., 2015; Naeem et al., 2016). Linkages between HWB and EH include direct and indirect paths and multiple feedbacks (Rogers et al., 2012). However, many indicators of HWB and EH lack obvious connections, and not all feedbacks are positive. For example, even as delivery of most ecosystem services is declining globally, human life expectancy and wealth are increasing (Millennium Ecosystem Assessment, 2005; Raudsepp-Hearne et al., 2010). A clearer understanding of linkages between HWB and EH could help managers of natural resources and human health better attain shared goals.

Human health is strongly linked to ecosystem services, a vast array of benefits that enable people to lead healthy, meaningful lives (Millennium Ecosystem Assessment, 2005); some even assert that human well-being is the ultimate ecosystem service (Sandifer et al., 2015). Major previously documented benefits provided by nature include those related to water and food supplies, psychological conditions, cognitive performance, disease rates, and cultural appreciation (Keniger et al., 2013; Hartig et al., 2014; Sandifer et al., 2015). Motivations to protect EH (and associated services) often include sense of place, hope for the future, and support for environmental protection (Rogers et al., 2012). Relationships between ecosystem and human health are often grounded in place-specific histories and cultures studied at the community or even individual scale (e.g., connections among land use, political structures, sense of identity, and health in Appalachia (Behringer and Friedell, 2006)). Commonly observed linkages among community race/ethnicity, economic status, and local pollution loads, whereby adverse exposures are greatest for poor or minority groups, are framed as issues of environmental justice (Cushing et al., 2015; Brulle and Pellow, 2006). Examining connections between EH and HWB at broad spatial scales may help inform state or national strategies to intentionally align regulations and programs so they simultaneously

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Abbreviations: %FCA, Percentage of stream kilometers with a fish consumption advisory; EH, Ecosystem health; HWB, Human well-being; HWBI, Human Well Being Index; VDEQ, Virginia Department of Environmental Quality; VSCI, Virginia Stream Condition Index.

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https://doi.org/10.1016/j.ecolind.2020.107194
Received 17 July 2020; Received in revised form 13 October 2020; Accepted 16 November 2020

promote EH, HWB, and environmental equity.

A broad array of indicators is used to characterize HWB and EH. Specific indicators of HWB range from mortality rates to perceptions of personal safety to levels of community engagement (Millennium Ecosystem Assessment, 2005; Summers et al., 2014). Characterizations of EH typically integrate suites of natural physicochemical and biological attributes (O`Brien et al., 2016). Specific indicators of EH range from contaminant burdens in wild animals to species diversity to rates of nutrient cycling (Angermeier and Karr, 2019). The fact that health of individuals (human versus nonhuman, respectively) is central to both concepts implies some indicators may be correlated.

HWB-EH relations are shaped by demographic and socioeconomic contexts, which often promote inequalities in HWB. It is widely recognized that low-income communities bear disproportionate exposures to polluted air and water (Morello-Frosch and Lopez, 2006; Downey and Hawkins, 2008; Landrigan et al., 2018); these exposures can be outcomes of systemic racism (Brulle and Pellow, 2006). These groups are often also excluded from the general benefits of maintaining or restoring healthy ecosystems (Dernoga et al., 2015; Villamagna et al., 2017). Further, exposure to contaminants via fish consumption can vary widely among ethnic groups (Stevens et al., 2018). Hitt and Hendryx (2010) showed that cancer mortality in West Virginia communities was negatively correlated with nearby stream health, but few other studies have examined relations between EH and human disease.

Herein, we examine spatial correlations among HWB, EH, and demographic factors in Virginia (eastern USA). We use stream health as a proxy for EH because surface waters are important points of human contact for pollutants and pathogens, and major sources of ecosystem services. Virginia's demographic and ecological diversity make it a good choice for our analysis. Virginia is racially diverse (30% non-White) and includes counties representing extremes in health (Khazan, 2015) and wealth (Sommeiller and Price, 2014). Ecosystem types and degrees of degradation vary widely from western Virginia's mountains easterly to the Atlantic Ocean. We presuppose that many feedback paths are plausible among HWB, EH, and demographic factors, but do not presume causality in our exploratory analysis. As stated previously, establishing causality would require finer-grained examinations of specific indicators in specific localities. Our analysis at the state scale instead seeks to document broader patterns across the social-ecological landscape and reveal questions that warrant more targeted study.

Table 1
Statistically significant Spearman's rho correlations between demographic and human well-being (HWB) indicators and two indicators of ecosystem health (VSCI and %FCA). HWB indicators are divided into three domains (see Table A.1). "ns" indicates $p > 0.05$; "*" indicates significance at $p \leq 0.05$; "**" indicates significance at $p \leq 0.01$. Bold italic indicates significance following a Holm-Bonferroni correction to account for Type I error.

Type	Variable	VSCI	% FCA
Demographics	% White	***0.508*****	ns
	Median age	0.326**	ns
	Population density	−0.321**	ns
	% Foreign born	ns	−0.220*
Human well-being indicators			
Health	Obesity prevalence	−0.312**	ns
	Diabetes prevalence	ns	0.183*
	Prevalence of mental or physical disabilities	ns	0.222*
	Cancer mortality	−0.268*	ns
	Infant mortality	−0.284**	ns
	Diabetes mortality	ns	0.175*
	Overall mortality	ns	***0.290*****
	Life expectancy	ns	−0.256**
Safety and security	Violent crime rate	−***0.387*****	0.252**
	Property crime rate	−0.280*	0.243**
Living standards	% Food insecure	−0.302**	0.232**
	Median household income	ns	−0.189*
	Median home value	ns	−0.238**

2. Methods

2.1. Measuring human well-being

We adopted the Human Well Being Index (HWBI; Smith et al., 2013, Summers et al., 2014) to characterize county-specific HWB. The HWBI was designed to be responsive to changes in flows of ecosystem services via relationships between its component metrics and human well-being. The HWBI comprises 79 indicators distributed among eight domains of social, economic, and cultural conditions (Appendix A, Table A.1). We located data with suitable spatial grain and timeframe from a variety of sources and tabulated 33 indicators representing six of the eight HWBI domains presented in Summers et al. (2014), which posits an extensive model for measuring HWB in the United States. Our indicators represented the domains of Health, Education, Safety and Security, and Living Standards better than the domains of Social Cohesion, Spiritual & Cultural Fulfillment, Connection to Nature, and Leisure Time. The spatial and temporal resolutions of our analyses were limited by the availability of HWB data that matched analogous resolutions of EH data. Although watersheds are a recommended spatial grain for analyzing environmental health data (Corley et al., 2018), we were forced to use counties as our spatial units of analysis. For indicators for which finer-grain data were available, we aggregated them at the county level. Because datasets varied in sample years and frequencies, we selected decade as our temporal unit of analysis and averaged data across the years 2006–2015 (the decade of greatest data availability). Additional methodological details are provided in Appendix A.

2.2. Measuring ecosystem health

We chose two inversely related indicators of stream condition to represent EH: the Virginia Stream Condition Index (VSCI) and the percentage of stream kilometers (per county) with a fish consumption advisory (%FCA). The VSCI is a multimetric index used by the Virginia Department of Environmental Quality (VDEQ) to monitor stream quality (Burton and Gerritsen, 2003). VSCI scores range from 0 to 100, with greater scores reflecting healthier streams. Our database of VSCI scores excluded data from large rivers and two coastal ecoregions (Middle Atlantic Coastal Plain and Southeastern Plains), which are assessed via different methodologies in Virginia. We analyzed data from 1053 VDEQ sites, covering 80 counties; collectively, these data represent stream health across most of Virginia (Appendix B, Fig. B.1). We averaged VSCI scores across all sites for each county so our measures of EH and HWB were spatially commensurate. While VSCI measures stream health, %FCA reflects a direct path of human exposure to contaminants. Advisories are issued by the VDEQ and/or the Virginia Department of Health when contaminant loads (e.g., metals, PCBs) in fish flesh exceed health limits for human consumption. We used data from VDEQ (2014), the only data available, to calculate %FCA for 133 counties (Appendix B, Fig. B.2). Additional methodological details are provided in Appendix B.

2.3. Measuring demographics

We selected four primary county-level demographic metrics: population density (number of people per square mile), percentage White (% White), percentage foreign-born (%Foreign-born), and median age. We expected population density to be inversely related to stream health, given the additional pressures on natural resources in densely populated areas. We also suspected that communities' median age might be related to EH, as people in different life stages might interact differently with surface waters. We selected racial and immigrant metrics to explore environmental inequity patterns. In subsequent analyses, we examined patterns for percentages of Black (%Black) and Hispanic/Latinx (%Hispanic). All demographic data came from the U.S. Census Bureau (2017).

2.4. Statistical analyses

We tested correlations and mean differences between selected pairs of indicators. We first conducted Spearman's rho correlation tests to assess relationships between HWB indicators, VSCI scores, %FCA, and demographic metrics. We then compared means of HWB and demographic indicators to specific thresholds in VSCI and %FCA. For VSCI, we chose a cut point of 61, the minimum passing score used by VDEQ. Streams in counties with average VSCI scores <61 are considered "impaired"; streams in counties with higher average VSCI scores are "not impaired." We compared means of HWB and demographic indicators between impaired versus not-impaired counties via t-tests. %FCA has no analogous threshold, so we calculated quartiles for those data. We then used analysis of variance to assess mean differences in HWB and demographic indicators among the lowest, two middle, and highest quartiles of %FCA values. Small sample sizes ($n = 80$ counties) precluded further analyses (e.g., regression).

3. Results

Both EH indicators (VSCI and %FCA) were significantly correlated with demographic and HWB indicators (Table 1). VSCI was higher in counties with a higher percentage of White residents, higher median age, and lower population density. Obesity prevalence, cancer mortality, infant mortality, violent and property crime, and food insecurity were all higher in counties with lower VSCI scores. VSCI was most strongly correlated with %White (positively) and violent crime rate (negatively; Table 1). VSCI and %White were higher on average in mountainous than in piedmont counties ($t = 2.3$, $p = 0.026$ and $t = 12.9$, $p < 0.001$, respectively). Region-specific correlations suggest the statewide correlation between VSCI and %White is not simply an artifact of spatial confounding. In the piedmont (68% White), the relation between VSCI and %White was similar to the statewide pattern ($\text{rho} = 0.496$; $p < 0.01$). However, this relation was weaker in the mountains, perhaps reflecting the lower racial and ethnic diversity there (92% White; $\text{rho} = 0.243$; $p = 0.16$).

To explore racial differences in more detail, we examined analogous correlations between the proportions of populations that were Black (%Black) and Hispanic/Latinx (%Hispanic) – the two most common non-White races in Virginia (20% and 10%, respectively) – versus VSCI scores and %FCA. %Black was negatively correlated with VSCI scores (Spearman's $\text{rho} = -0.363$; $p < 0.001$), while %Hispanic did not exhibit a statistically significant relationship. %Hispanic was weakly associated with lower %FCA (Spearman's $\text{rho} = -0.204$; $p = 0.02$), while %Black did not exhibit a statistically significant relationship.

%FCA was more frequently correlated with HWB indicators than VSCI, but %FCA correlations tended to be weaker (Table 1). Only three HWB indicators (two crime rates and food insecurity) were correlated with both EH indicators. %FCA was higher in counties with higher diabetes prevalence and mortality, disability prevalence, overall mortality, violent and property crime, and food insecurity, but lower in counties with greater life expectancy, median household income, and median home value. %FCA was most strongly correlated with overall mortality ($\text{rho} = 0.290$; $p < 0.01$; Table 1), which was generally highest in the coalfield counties of southwestern Virginia. Region-specific analyses indicated significant inverse relations between %White and %FCA in the mountains ($\text{rho} = -0.354$; $p = 0.018$) and coastal plain ($\text{rho} = -0.359$; $p = 0.018$), but not in the piedmont ($\text{rho} = -0.162$; $p = 0.287$).

To probe these correlations further, we compared HWB and demographic factors between impaired versus not-impaired counties for VSCI. Counties where streams were mostly impaired had proportionally fewer white residents, more food insecurity, higher rates of obesity, lower life expectancies, and higher overall mortalities; %White exhibited the greatest difference, with a moderate-to-large Cohen's d effect size (0.79; Appendix C, Table C.1). We also compared HWB and demographic factors across quartiles of %FCA. Counties with high %FCA had proportionally fewer White and foreign-born residents, higher rates of property and violent crime, more food insecurity, and higher rates of Alzheimer's and overall mortality; overall mortality exhibited the most robust difference (Table C.2).

4. Discussion

Linkages between HWB and EH are complex and indicator-dependent. Our EH indicators were positively correlated with distinctive subsets of HWB indicators across three domains (Table 1). Others have documented correlations between human and stream health (e.g., Hitt and Hendryx, 2010), but analyses remain too sparse to draw general conclusions about the strengths or causal directions of HWB-EH linkages, especially since the relationship between some HWB indicators and EH may be indirect or the result of confounding correlates (Millennium Ecosystem Assessment, 2005; Rogers et al., 2012; our Table 1). For example, we found some non-health indicators of HWB (i.e., violent crime rate and food insecurity) were inversely related to EH (Table 1). Further research to identify responsible mechanisms and pathways is highly warranted, and we suspect EH does not necessarily drive such correlations. Previous research (e.g., Cushing et al., 2015; Brulle and Pellow, 2006) suggests there are feedbacks through which poor EH exacerbates background inequities in socioeconomic and political factors. For example, communities struggling with high rates of crime, violence, and poverty may lack the avenues of communication and influence within existing sociopolitical and financial structures to improve their local EH. Notably, empirical studies suggest ecosystem improvements (e.g., adding green space) can help reduce crime and improve public health (Kondo et al., 2015; Bogar and Beyer, 2016).

Causal linkages between HWB and EH – not just correlations – are critical for informing effective management of ecosystem and/or public health. Though our findings highlight several topics that warrant future study (e.g., potential links between EH and systemic racism and between contaminants and mortality), understanding causation will require more fine-grained spatiotemporal analyses to reveal the specific pathways and feedbacks linking HWB and EH. For example, a direct causal link from %FCA to mortality rate would require confirmation that people eat enough local contaminated fish to diminish their health. Our analysis lacked data on the frequency with which people consumed (or even touched) fish or water from their county's streams. Causal links between a person's health and her interactions with nature are complex, precluding straightforward interpretations of correlations. People interact with nature in many disparate ways, thereby affecting various health consequences (Keniger et al., 2013). Assessments of links between health and nature typically have focused on specific experiences (e.g., with greenspace) and/or benefits (e.g., psychological) (see reviews by Keniger et al., 2013; Hartig et al., 2014; Sandifer et al., 2015) rather than on outcomes of eating or drinking ecosystem contaminants.

The knowledge of HWB-EH linkages needed to inform managers of ecosystem and public health will require more innovative multidisciplinary, multiscale studies that span the natural and social sciences (Dunham et al., 2018). Our work was limited by the spatiotemporal scales of available data, demonstrating the need for careful collection and curation of spatially and temporally commensurate data on key EH and HWB indicators. Such data, if examined over time, could help determine if improvements in EH, such as those resulting from implementation of Clean Water Act policies (Zhang et al., 2018), subsequently drive improvements in HWB. The socioeconomic benefits of ecosystem management programs are commonly assessed over large spatiotemporal extents (e.g., Phillips and McGee, 2014) but finer-scale assessments (e.g., for individual communities or households) are rare. Alternatively, improvements in local EH may be outcomes of certain configurations of HWB attributes, such as community pride, engagement in governance, and socioeconomic status.

Influences of demographic factors such as race complicate our understanding of HWB-EH relationships. Current disparities in the environmental quality experienced by racial groups may reflect differences in political efficacy, economic influence, and/or settlement history. The strength of the correlation we observed between VSCI and %White was striking despite the data and statistical limitations of our exploratory analysis. Given extensive past research demonstrating that minorities in other regions are more likely to live in polluted or degraded environments, leading to impaired health or life expectancy (Morello-Frosch and Lopez, 2006; Downey and Hawkins, 2008; Landrigan et al., 2018), we see explication of the factors underpinning this observation in Virginia as a top research priority. Black residents, in particular, appear to more commonly live in areas with poorer VSCI scores, while Hispanic/Latinx residents tend to live in areas where fish consumption advisories are less widespread. Each trend may represent environmental inequity but it is unclear whether the observed spatial variance in EH reflects differences in pollution loads, environmental monitoring, regulatory enforcement, political empowerment, or other factors. Rigorous examinations of linkages among HWB, EH, and demographics could inform investment in environmental programs to enhance cost-effectiveness and equity, and perhaps avoid demographic disparities in environmental outcomes such as those observed in Maryland's watershed restoration programs (Dernoga et al., 2015).

5. Conclusions

Demonstration of empirical linkages between HWB and EH, over a range of spatiotemporal scales, may better inform or motivate management of public and ecosystem health. We demonstrated statistically significant correlations between some indicators of HWB – reflecting human health, safety and security, and living standards – and measures of EH across Virginia. Though our exploratory analysis cannot establish causation, the consistency of these findings with prior studies underscores the need for further research, particularly related to understanding potential environmental inequities and the roles of contaminants in human disease. We call for multidisciplinary, multiscale studies to examine the toxicological, epidemiological, socioeconomic, and political dimensions of EH-HWB relations. We expect a key scientific limitation to be the availability of data on topics such as how people interact with local ecosystems; therefore, future intentional collection of HWB and EH data on commensurate spatiotemporal scales is essential. Ideally, geostatistical examinations of monitoring data would be accompanied by intensive examinations of community and individual lived experiences to uncover place-specific drivers of disparities in HWB and EH, as well as opportunities for improving them. Research that articulates the benefits of healthy ecosystems might bolster public support for environmental protection, and thereby facilitate management of landscapes that promote positive interactions between people and nature.

CRediT authorship contribution statement

Paul L. Angermeier: Conceptualization, Methodology, Writing - original draft, Project administration, Funding acquisition. **Leigh Anne Krometis:** Conceptualization, Methodology, Writing - original draft, Funding acquisition. **Marc J. Stern:** Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft, Visualization, Funding acquisition. **Tyler L. Hemby:** Methodology, Formal analysis, Data curation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Our data are available in the databases cited in the References sections. This work was funded by three Virginia Tech programs: Center for Global Change; Institute for Society, Culture, and the Environment; and Fralin Life Science Institute. We thank Larry Willis for his comments on study design and the manuscript. The Virginia Cooperative Fish and Wildlife Research Unit is jointly sponsored by the U.S. Geological Survey, Virginia Tech, Virginia Department of Wildlife Resources, and Wildlife Management Institute. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Appendix A. Indicators of human well-being.

A.1 Measuring human well-being

Current assessments of HWB typically adopt multimetric indexes to account for a wide range of contributing components, but there is no standard protocol. We adopted the Human Well Being Index (HWBI), developed by the U.S. Environmental Protection Agency, as our comprehensive starting template (Smith et al., 2013; Summers et al., 2014). The HWBI was designed to measure county-specific HWB and be responsive to changes in the flows of ecosystem services via relationships between component metrics and economic, environmental, and social well-being. The HWBI comprises 79 indicators distributed among eight domains of social, economic, and cultural conditions (Table A.1). A main strength of the HWBI is that it distinguishes between HWB itself and its drivers (e.g., freedom of choice, effective governance), which are excluded from computations.

We located data for 33 indicators representing six of the eight domains of HWB identified by Summers et al. (2014) (Table A.1). Data for additional suggested indicators were not available at the county level or finer grain for our analytical timeframe. We collected HWB data (in multiple formats and resolutions) from a variety of federal, state, academic, and non-profit organizations (Table A.1). The four domains of Health, Education, Safety and Security, and Living Standards were well represented by multiple indicators. However, Social Cohesion and Spiritual & Cultural Fulfillment were represented by only one or two indicators, and we found no available indicators of Connection to Nature or Leisure Time.

Ideally, analyses of relations between HWB and EH would be based on data collected frequently and synchronously. While waterbody-specific data on EH were available (i.e., stream assessments), the spatial and temporal resolutions of our analyses were limited by the availability of HWB data. Numerous recent studies recommend collecting environmental health data at spatial grains commensurate with likely exposures (e.g., watersheds), though these studies also recognize the constraints sometimes posed by available data (Corley et al., 2018). Such constraints forced us to use political boundaries (i.e., counties) to define our minimum spatial units of analysis. If finer-grain data were available, we aggregated all measures at the county level to minimize spatial bias. Herein, we use "county" to mean county or city, as Virginia distinguishes between counties and cities in its data summaries. Because datasets varied widely in sample years and frequencies, and because we expected some HWB-EH relations to manifest over long timespans, we selected decade as our temporal unit of analysis and averaged available data across the years 2006–2015, which represented the decade of greatest data availability.

Table A1

List of eight domains of human well-being indicators, suggested indicator categories from Summers et al. (2014), and the actual indicators used in this study. *Physical inactivity, which we considered a "Lifestyle and behavior" indicator, is also related to leisure time, but inversely. N/A indicates we could find no suitable data for our analysis.

Domain	Suggested indicators	Data used herein	Description	Source	Years available
Connection to nature	Biophilia	N/A	N/A	N/A	N/A
Cultural fulfillment	Activity participation	Rate of congregational adherence	Religious adherence (per 1,000) for 236 religious groups	Association of Religious Data Archives (2017)	2010
Education	Basic educational knowledge and skills of youth	Math skills; reading skills; science skills	Average test scores (3rd-8th grade) on State Standards of Learning tests	Virginia Department of Education (2017)	2006–2015
	Participation and attainment	Educational attainment	Weighted education attainment (1–5 score, weighting based on proportion in each category: 1. No high school diploma; 2. High school diploma or GED; 3. Some college/ associate's degree; 4. Bachelor's degree; 5. Graduate/ professional degree.	U.S. Census, American Communities Survey (2017)	2009–2015
		Post-secondary enrollment	% of high school graduates enrolled in post-secondary education	Virginia Department of Education (2017)	2008–2014
	Social, emotional, and developmental aspects	Bullying	Bullying rate (per 10,000 students)	Virginia Department of Education (2017)	2011–2015
Human health	Healthcare	Satisfaction with healthcare	% of patients who rated satisfaction with hospital stay 9 or 10 (out of 10)	U.S Department of Health and Human Services (2018)	2008–2015
	Life expectancy and mortality	Life expectancy	Life expectancy estimate by county	University of Washington Institute for Health Metrics and Evaluation (2013)	2006–2010
		Mortality rates: Alzheimer's; cancer; diabetes; heart disease; infant; kidney disease; respiratory disease; suicide; overall	Deaths per 100,000 (age adjusted)	Centers for Disease Control and Prevention (2017)	2006–2015
	Lifestyle and behavior	Physical inactivity prevalence	% of population engaging in no physical activity or exercise in the past month other than for job	Centers for Disease Control and Prevention (2017)	2006–2013
	Personal well-being	N/A	N/A	N/A	N/A
	Physical and mental health conditions	Physical or mental disability	% of population	U.S. Census, American Communities Survey (2017)	2011–2015
		Prevalence: diabetes, obesity	% of population	Centers for Disease Control and Prevention (2016)	2006–2013
Leisure time*	Activity participation; time spent by working-age adults	N/A	N/A	N/A	N/A
Living standards	Basic necessities	Food insecurity	Estimated % of population designated as "food insecure"	Gundersenet al. (2018)	2011–2014
		Housing affordability	Median monthly owner cost as % of household income	N/A	N/A
	Income	Median household income	Median annual household income ($)	U.S. Census, American Communities Survey (2017)	2009–2015
		Poverty	% of population living below poverty line	U.S. Census, American Communities Survey (2017)	2006–2015
	Wealth	Median home value	Median home value ($)	U.S. Census, American Communities Survey (2017)	2009–2015
		Mortgage debt	% of owner-occupied housing with mortgage debt	U.S. Census, American Communities Survey (2017)	2009–2015
		N/A	N/A	N/A	N/A

(*continued on next page*)

Table A1 (*continued*)

Domain	Suggested indicators	Data used herein	Description	Source	Years available
	Job quality and satisfaction				
Safety and security	Actual safety	Accidental mortality	Accidental mortality rate (per 100,000): deaths from all external causes (e.g., accidents, homicides, natural disaster)	Centers for Disease Control and Prevention (2017)	2006–2015
		Property crime	Property crime rate (per 100,000): burglary, larceny, motor vehicle theft, arson	Institutional Consortium for Political and Social Research (2017)	2006–2015
		Violent crime	Violent crime rate (per 100,000): murder, rape, robbery, aggravated assault		2006–2015
	Perceived safety	N/A	N/A	N/A	N/A
	Risk	Social vulnerability index	Index of socio-demographic variables related to resilience to natural hazards	University of South Carolina Hazards & Vulnerability Institute (2017)	2006–2014
Social cohesion	Attitude toward others; family bonding; social engagement; social support	N/A	N/A	N/A	N/A
	Democratic engagement	Voter turnout	Voter turnout (% of population age 18 +)	Virginia Department of Elections (general elections, November 2017)	2008–2015
		Registered voters	Registered voters (% of population age 18 +)	Virginia Department of Elections (December 2017)	2008–2015

Appendix B. Indicators of ecosystem health.

B.1 Measuring ecosystem health

Current assessments of EH typically adopt multimetric indexes to account for a wide range of contributing components, but there is no standard protocol to assess EH for large regions. Virginia regularly and extensively assesses the ecological health of its surface waters in accordance with the regulatory requirements of the U.S. Clean Water Act. Because aquatic biota integrate outcomes of a broad suite of potential anthropogenic impacts across catchments and through time, assessments of the condition of instream biotic communities are common proxies of overall EH.

We chose two theoretically inversely related measures of stream condition to represent EH: the Virginia Stream Condition Index (VSCI) and the percentage of stream kilometers (per county) with a fish consumption advisory (%FCA). The VSCI comprises eight metrics representing taxonomic composition and diversity, pollution tolerance, and trophic composition of the benthic macroinvertebrate community. This index, which is analogous to instream health indexes developed by most states, is used by the Virginia Department of Environmental Quality (VDEQ) to inform its regulatory requirements to maintain the quality and designated uses of surface waters (Burton and Gerritsen 2003).

Virginia follows standard regional procedures for biological monitoring (Barbouret al., 1999; Virginia Department of Environmental Quality, 2008). VSCI scores range from 0 to 100, with greater scores reflecting healthier streams. We acquired from VDEQ a “clean” database of VSCI scores; the database excluded replicate data and data from large rivers, which are assessed via different, non-comparable methodology. We also excluded data from the two coastal ecoregions (Middle Atlantic Coastal Plain and Southeastern Plains), because those VSCI scores are incompatible with scores from other ecoregions of Virginia due to differences in ecological conditions and scoring methodology (Jason Hill [VDEQ], personal communication; Govenor et al., 2018).

We analyzed data from sites selected by VDEQ for monitoring via probabilistic (802 sites) and comprehensive (251 sites) sampling efforts, which covered 80 counties. Sites selected by VDEQ for other monitoring purposes (e.g., pristine reference sites, known polluted sites, or special project sites) were excluded to avoid potential bias. Probabilistic sites, with randomly chosen locations, are established to facilitate an extrapolated spatial analysis. Comprehensive sites are not randomly located but are distributed to collectively measure stream health across Virginia. We averaged VSCI scores across all probabilistic and comprehensive sites for each county to render this measure of EH spatially commensurate with our measures of HWB. For sites located within 100 m of a political boundary, we attributed data to both counties (i.e., sites were included in two averages of VSCI scores). One county (Highland) and several cities lacked VSCI data, and were excluded from our analysis (Fig. B.1).

While VSCI measures overall stream health, %FCA reflects impairment of a particular ecosystem service – safe-to-eat wild fish – and postulates a direct path of human exposure to contaminants (i.e., consuming fish). Advisories are issued by the VDEQ and/or the Virginia Department of Health when contaminant loads (e.g., metals, PCBs) measured in fish tissue exceed health limits for human consumption. At any given time, dozens of Virginia waters may have advisories in force (Angermeier and Pinder, 2015). To calculate %FCA for each county, we used data from VDEQ (2014) in conjunction with a shapefile of Virginia counties. The only %FCA data available were from 2014; we included 133 counties in our analyses (Fig. B.2).

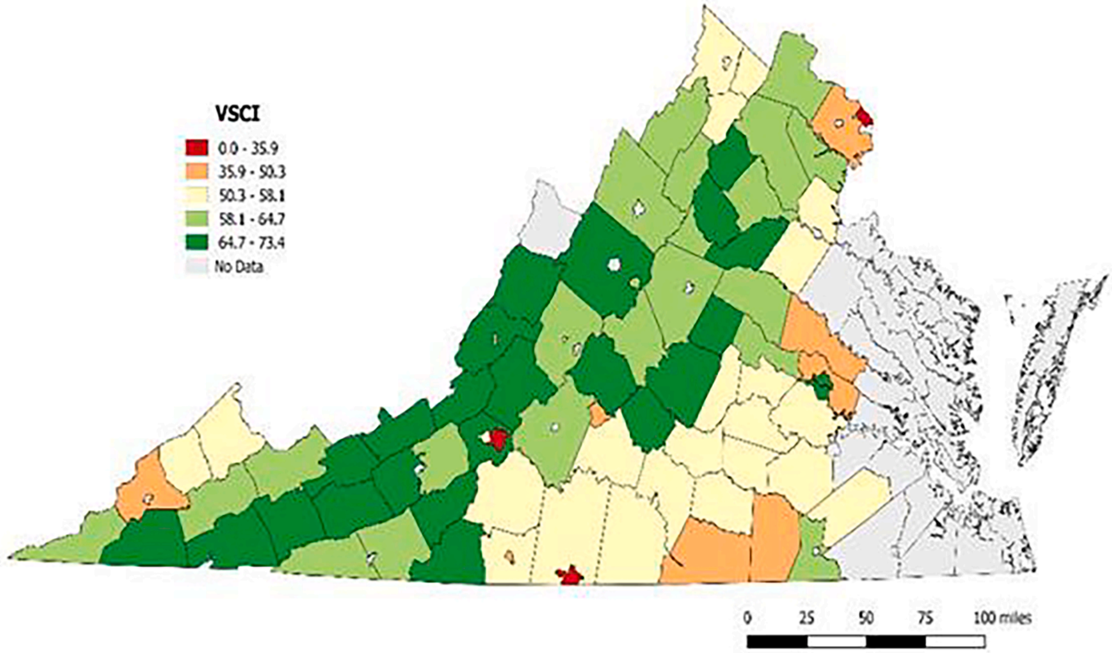

Fig. B1. Map of county-specific values of Virginia Stream Condition Index (VSCI) scores. The "No data" counties lacked VSCI data.

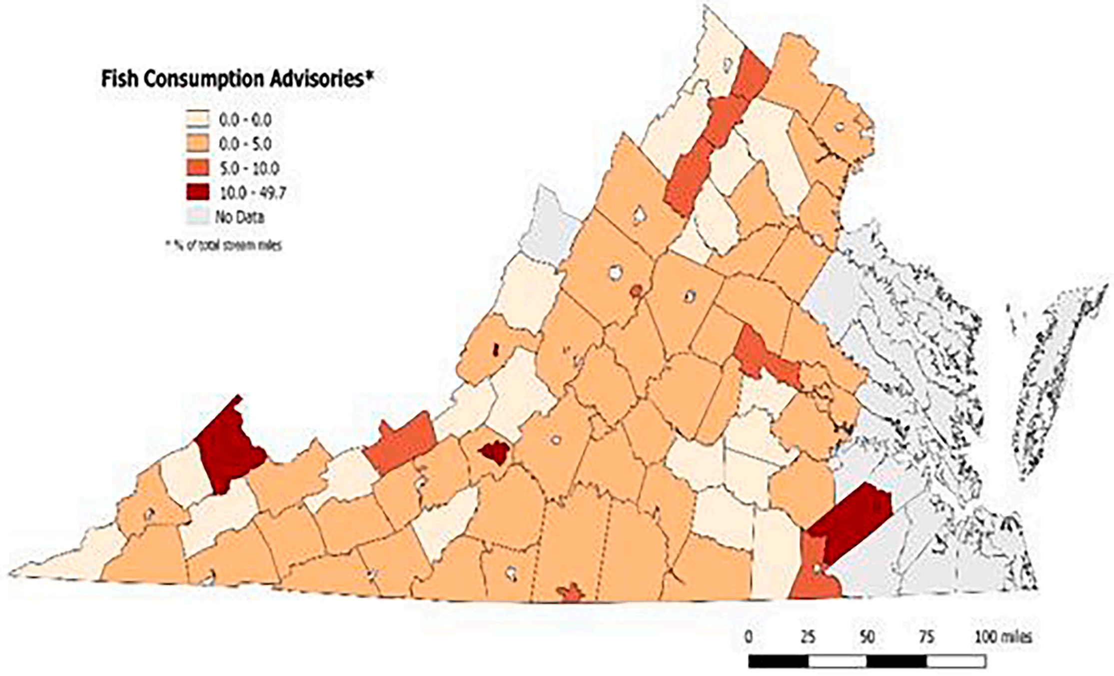

Fig. B2. Map of county-specific values of extent of fish consumption advisories. The "No data" counties lacked advisory data.

Appendix C. . Mean differences for indicators.

Table C1

Comparisons of means (t-tests) of selected demographic and human well-being indicators between counties with impaired (n = 36) versus not impaired (n = 44) streams, based on VSCI scores. Bold italic indicates significance following a Holm-Bonferroni correction to account for Type I error.

Indicator	Impairment	Mean	t	p	Cohen's d
%White	Not impaired	86.4	−3.6	***< 0.001***	−0.79
	Impaired	74.7			
%Food insecure	Not impaired	10.8	2.9	0.005	0.64
	Impaired	13.2			
Obesity prevalence	Not impaired	28.2	2.5	0.014	0.57
	Impaired	29.6			
Life expectancy	Not impaired	77.2	−2.1	0.040	−0.49
	Impaired	76.2			
Overall mortality	Not impaired	804.3	2.0	0.049	0.46
	Impaired	861.7			

Table C2

Comparisons of means (ANOVAs) of selected demographic and human well-being indicators among counties with low (<0.85%), medium (0.85%-3.75%), and high (>3.75%) %FCA. Means with the same superscript are not statistically different. * indicates significance at $p < 0.10$ for the post-hoc test. Bold italic indicates significance following a Holm-Bonferroni correction to account for Type I error.

Indicator	Tests	Low	Medium	High	F/ Welch	p
Overall mortality	One-way ANOVA; Tukey posthoc	805.9^{a}	815.9^{a}	899.2^{b}	7.1	***0.001***
Violent crime	Welch's ANOVA; Dunnett's C posthoc	180.8^{a}	152.8^{a}	291.9^{b}	5.6	0.005
%Food insecure	Welch's ANOVA; Dunnett's C posthoc	12.1^{a}	11.8^{a}	15.0^{b}	5.5	0.006
Alzheimer's mortality rate	Welch's ANOVA; Dunnett's C posthoc	$12.0^{a,b}$	8.2^{a}	16.6^{b}	5.1	0.009
Property crime	Welch's ANOVA; Dunnett's C posthoc	1899.9^{a}	1753.8^{a}	2692.7^{b}	4.8	0.011
%White	Welch's ANOVA; Dunnett's C posthoc	$76.3^{a,b}$	81.7^{a}	69.2^{b}	4.5	0.014
%Foreign born*	Welch's ANOVA; Dunnett's C posthoc	6.3^{a}	3.6^{b}	3.7^{b}	3.4	0.038

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