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Special Feature: Broadening perspectives

Differential equity in access to public and private coastal infrastructure in the Southeastern United States

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Abstract

Despite the ubiquity of coastal infrastructure, it is unclear what factors drive its placement, particularly for water access infrastructure (WAI) that facilitates entry to coastal ecosystems such as docks, piers, and boat landings. The placement of WAI has both ecological and social dimensions, and certain segments of coastal populations may have differential access to water. In this study, we used an environmental justice framework to assess how public and private WAI in South Carolina, USA are distributed with respect to race and income. Using publicly available data from State agencies and the US Census Bureau, we mapped the distribution of these structures across the 301 km of the South Carolina coast. Using spatially explicit analyses with high resolution, we found that census block groups (CBGs) with lower income are more likely to contain public WAI, but racial composition has no effect. Private docks showed the opposite trends, as the abundance of docks is significantly, positively correlated with CBGs that have greater percentages of White residents, while income has no effect. We contend that the racially unequal distribution of docks is likely a consequence of the legacy of Black land loss, especially of waterfront property, throughout the coastal southeast during the past half-century. Knowledge of racially uneven distribution of WAI can guide public policy to rectify this imbalance and support advocacy organizations working to promote public water access. Our work also points to the importance of considering race in ecological research, as the spatial distribution of coastal infrastructure directly affects ecosystems through the structures themselves and regulates which groups access water and what activities they can engage in at those sites.

KEYWORDS

coastal infrastructure, environmental justice, GIS, spatial equity, spatial regression, water access

INTRODUCTION

Societies have modified shorelines for centuries to utilize, augment, and control the ecosystem services provided by coastal environments (Dugan et al., 2011). Structures like docks, boat landings (ramps), marinas, and piers facilitate access to water, modulating where and how humans interact with coastal ecosystems. We collectively refer to these types of structures as "water access infrastructure" (WAI), which can be either publicly or privately owned. WAI fulfills multiple roles for coastal populations. They provide recreation, space to observe and enjoy coastal ecosystems, and influence how people interact with marine environments by providing spaces to harvest seafood resources.

The distribution of public and private WAI serves as a quantifiable index of who has access to coastal ecosystem services. In this article, we define access as the ability to physically enter the marine environment (Ribot & Peluso, 2003; Schlager & Ostrom, 1992). Most States in the USA (Frank, 2011) and many other countries (Blumm & Guthrie, 2011) legally recognize all navigable waterbodies and areas below mean high water as public property; however, all waters are not functionally public. Long stretches of private property along the water/land interface (the "upland") can prevent water access. Thus, for those who do not possess their own private WAI, the ability to enter coastal waters is primarily determined by the availability of public WAI. This potential disconnect between the legal and functional status of defined waterbodies emphasizes the importance of examining the socioeconomic distribution of public and private WAI.

Focusing on who has access to water through WAI can be investigated under the framework of environmental justice (EJ). EJ is an activist and scholarly movement that arose from grassroots organizing against environmental racism, the unequal distribution of environmental benefits and burdens along racial lines (Bullard & Johnson, 2000; Taylor, 2014). Although EJ coalesced around the human health impacts of toxic industries and waste sites (Bullard et al., 2008; Mohai et al., 2009; Ringquist, 2005), it has expanded in recent decades to encompass a wider range of human–environment interactions. Among these, the equitable distribution of ecosystem services is an emerging and important subfield. Dominant research topics in this area include access to greenspaces such as parks and trails for leisure (Rigolon, 2017; Suárez et al., 2020; Wolch et al., 2014), availability of safe drinking water (Heck, 2021; Ranganathan & Balazs, 2015; Schaider et al., 2019), and the distribution of regulating services such as heat mitigation and carbon sequestration provided by urban tree canopy cover (Jenerette et al., 2011; Riley & Gardiner, 2020; Schwarz et al., 2015). Racial (Pulido, 2016; Rigolon, 2017; Riley & Gardiner, 2020; Schaider et al., 2019) and economic disparities (Jenerette et al., 2011; Kim et al., 2019; Schwarz et al., 2015) have been documented in the distribution of ecosystem services, although the relative strength of racial and economic disparities vary depending on context and is strongly influenced by local history (Riley & Gardiner, 2020).

Although natural resource management is increasingly viewed through the lens of EJ, few studies have examined the justice dimensions of access to coastal ecosystems and the availability of public WAI (Kim et al., 2019; Montgomery et al., 2015; Paloniemi et al., 2018; Pitt, 2019). Availability can be measured through several metrics, including simple counts of public WAI in an area or the distance individuals must travel to reach public WAI (Haeffner et al., 2017; Kim et al., 2019). In Miami, Florida, Montgomery et al. (2015) found that race, ethnicity, and economic status affected public beach access, as non-Latinx White and higher income neighborhoods were significantly closer to public beaches than other neighborhoods. Working in Helsinki, Finland, Paloniemi et al. (2018) found physical, transportation, and legal barriers to accessing public beaches across the city, although they did not directly evaluate the effects of race, income, or other socioeconomic factors. These studies highlight the importance of assessing the availability of public access to coastal environments and to contextualize this within the broader landscape of private water access.

Considering the scarcity of research into the factors that control the distribution of water access in both the ecological and EJ literature, we used mapping and regression to examine the following question: How are public WAI (boat landings and piers) and private WAI (docks) distributed across economic and racial groups along the coast of South Carolina? We hypothesize that private WAI abundance and the probability that a census block group (CBG) will contain any public WAI will be positively correlated with median household income and the proportion of the population that is White. Likewise, we predict that the average distance to the nearest public WAI will be negatively correlated with median household income and the percentage of the population that is White. We consider the likelihood of containing public WAI and the distance to the nearest public WAI as different metrics for assessing availability. In short, we predict wealthy areas with a higher proportion of White residents will contain a greater abundance of private WAI, be more likely to have any public WAI, and will be closer to public WAI than lower income areas with a higher proportion of non-White residents.

Our study contributes to the growing literature on EJ and natural resource access by providing one of the first large-scale spatial assessments of public and private WAI distribution. Investigating who can utilize WAI has important implications for ecology and coastal management, as different racial and ethnic groups consume self-caught seafood at different rates (Burger et al., 1999; Ellis et al., 2014), prioritize and collect different species (Hunt & Ditton, 2002), and use different techniques and gear (Brown & Toth Jr., 2001). Thus, understanding where these structures are on the landscape and who can readily use them illuminates the patterns of access to natural resources and can improve our understanding of impacts on resources.

METHODS

Study system

We conducted our research in six coastal counties of the southeastern State of South Carolina (Figure 1, inset map). Counties are geographic subdivisions of a State that have their own local governments. The coastal portions of these counties are characterized by salt marshes, which is typical of the southeast USA, while interior portions of these counties contain freshwater and brackish tidal rivers. All areas below mean high water are legally defined as public property in South Carolina, but this does not guarantee functional water access. Without a boat, navigable

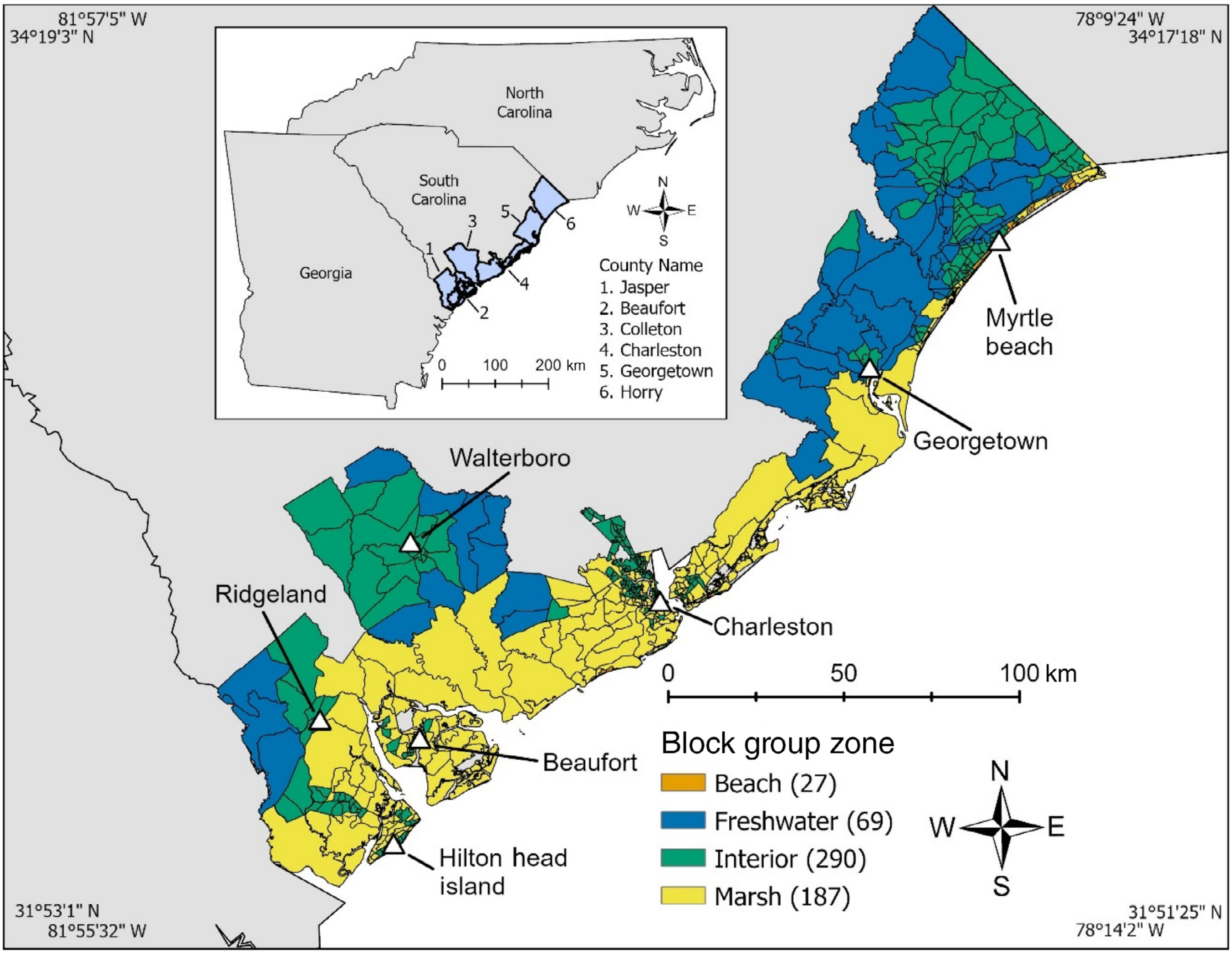

FIGURE 1 Main map shows census block groups (CBG) and zone classification for the study area in coastal South Carolina in the southeastern USA. Numbers in the legend represent the number of CBGs in each zone. Inset map (top left) shows South Carolina and neighboring States, along with a numbered legend for the six coastal counties. Major cities in South Carolina are marked by white triangles and associated text. Main map scale 1:1,250,000; county inset map scale 1:8,250,000. CBGs in the Beach Zone are small and may be difficult to discern at the scale of the full study area.

saltwater/freshwater rivers are only accessible from public WAI or the upland, which can be privatized and block access to waters.

South Carolina is an advantageous study system because WAI data were readily available for all six counties and these counties are both racially and economically diverse, which allows a robust analysis of WAI distribution. Furthermore, part of our decision to locate our study in South Carolina was based on the writings and experiences of Gullah-Geechee authors and their colleagues (Campbell, 2011; Ellis et al., 2014; Goodwine, 2015; Hoke & Watson, 2013). The Gullah-Geechee are descendants of formerly enslaved African peoples, largely from West-Central Africa who formed their own language, cultural practices, and livelihood systems along the coast from Jacksonville, Florida to Jacksonville, North Carolina (Ellis et al., 2014; Goodwine, 2015; Zimmerman et al., 2021). Today, there are an estimated 200,000 people of Gullah-Geechee heritage living in the coastal counties of North Carolina, South Carolina, Georgia, and Florida (NPS, 2005), although the Gullah-Geechee diaspora throughout Northern America, Central America, and the Caribbean is undoubtedly much larger (Campbell, 2011). Furthermore, social stigma and racism against the use of the Gullah-Geechee language throughout the 20th century (Campbell, 2011; Jones-Jackson, 1978) led to many communities not recognizing themselves as Gullah-Geechee (Campbell, 2011; Cooper, 2017), resulting in a likely underestimate of people of Gullah-Geechee descent in the coastal southeast. The Gullah-Geechee are a federally recognized cultural group that has deep ties to and knowledge of the socioecological systems of South Carolina and other southeastern States. Seafood gathering is particularly important to the Gullah-Geechee in this region, and many rely on the resources from marshes for subsistence, economic, and cultural uses (Beoku-Betts, 1995; Ellis et al., 2014; Goodwine, 2015; Gullah-Geechee Cultural Heritage Corridor Commission, 2012).

Defining the study area

We conducted our analysis at the CBG level. The United States Census Bureau subdivides counties into smaller geographic units known as census tracts, which are themselves divided into CBGs, designed to encompass between 600 and 3000 people. Census tracts and CBGs do not represent political jurisdictions but are used by the Census Bureau to summarize and report demographic data. CBGs represent the highest spatial resolution for demographic data in most situations and are routinely used in EJ research (Riley & Gardiner, 2020; Schwarz et al., 2015).

We downloaded shapefiles for the 583 CBGs that made up our focal counties from the Census Bureau TIGER/Line Shapefile website (https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html). Because we are only interested in residential and public areas, we removed six CBGs that encompassed military bases and three CBGs that made up the Port of Charleston. We also removed one CBG in Horry County because it consisted of small docks on manufactured canals that are not reflective of development patterns anywhere else on the South Carolina coast. After removing these block groups, our final, full study area consisted of 573 CBGs.

We divided our study area into "Beach," "Freshwater," "Interior," and "Marsh" Zones (Figure 1) following the saltwater/freshwater dividing line from the South Carolina Department of Natural Resources (https://www.dnr.sc.gov/marine/dividingline.html) and official beachfront jurisdictional lines from the South Carolina Department of Health and Environmental Control (DHEC, https://gis.dhec.sc.gov/shoreline/). We classified CBGs with more than 1 km of marsh/saltwater shoreline as part of the Marsh Zone, CBGs with greater than 0.25 km of beach shoreline and less than 1 km of marsh shoreline as part of the Beach Zone, and CBGs with more than 1 km of freshwater river shoreline as part of the Freshwater Zone. We classified all other CBGs in the study area as part of the Interior Zone. We chose a 1 km minimum shoreline length to define the Freshwater and Marsh Zones to ensure we were only selecting CBGs with appreciable levels of shoreline, as we observed that many CBGs with low lengths of shoreline consisted of small embayments that did not contain navigable water (Appendix S1).

Objectives

We addressed our research question through four objectives: (1) enumerate, visualize, and quantify the density of public and private WAI across the entire 573 CBG region; (2) analyze the likelihood a CBG will contain any public WAI with respect to the racial and economic composition across the 283 CBGs of the Beach, Freshwater, and Marsh Zones; (3) analyze the distance to the nearest public WAI across the 283 CBGs of the Beach, Freshwater, and Marsh Zones; and (4) analyze the abundance of private WAI with respect to the racial and economic composition across the 187 CBGs of the Marsh Zone.

Data collection: Response variables

We collected data on public and private WAI abundance for Objectives 1, 2, and 4 from shapefiles of WAI from DHEC's public GIS server (https://sc-department-of-health-and-environmental-control-gis-sc-dhec.hub.arcgis.com/). These shapefiles contained digitized outlines of boat landings, docks, and piers that we cross-referenced with city and county websites to verify and distinguish between public (piers and boat landings) and private (docks) infrastructure. We counted and recorded how many of each structure type was present within each CBG in ArcMap 10.6.1 (ESRI, 2018) at a 1:1500 scale. For Objective 3, we used the "Cost Distance" tool in ArcMap to measure the distance to the nearest public WAI along a shapefile of roads and highways from the South Carolina Department of Transportation's public GIS website (http://info2.scdot.org/GISMapping/Pages/GIS.aspx). We then extracted distance values for 100 randomly placed points per CBG along that road network, with a minimum distance of 10 m separating each point. We averaged these extracted values to get a mean distance to nearest public WAI for each CBG.

Data collection: Predictor variables

Because WAI are necessarily built along bodies of water, we measured the length of shoreline of each block group in ArcMap. We measured shoreline using 30 m resolution land cover rasters from NOAA's Digital Coast portal (https://coast.noaa.gov/digitalcoast/data/) and labeled each shoreline segment as either "Beach," "Marsh," or "Freshwater" following the same saltwater/freshwater and beachfront lines discussed above (Appendix S1: Figures S1 and S2). Freshwater ponds and wetlands are also important natural resource areas, particularly for the Gullah-Geechee (Halfacre et al., 2010; Hurley & Halfacre, 2011), but they are beyond the scope of this study, and we did not include them in the measure of shore length.

We gathered data on demographic predictors from the American Community Survey (ACS) that the United States Census Bureau administers in the years between decennial censuses and models demographic characteristics from a yearly sample of ~3.5 million households across the USA. We collected data from the 2012–2016 5-year average using the R package "tidycensus" (Walker & Herman, 2021) in R v.4.0.4 (R Core Team, 2021) to correspond with the published date of the WAI data. We used median household income as a measure of CBG economic status and the percentage of the CBG population classified as White by the Census Bureau as a measure of racial composition. We chose to represent racial composition through the percentage White variable because White and Black residents were by far the most prevalent racial groups across the zones used in the analysis (Figure 2a,b). Because the Census Bureau does not collect data that allow us to distinguish Gullah-Geechee from Black residents who are not of Gullah-Geechee heritage, we cannot directly analyze the distribution of WAI with respect to Gullah-Geechee communities. Despite this limitation, the Gullah-Geechee comprise a large share of the Black population in coastal South Carolina given their long history in the area (Goodwine, 2015; Zimmerman et al., 2021).

We selected additional predictor variables, percentage homeownership and total population, based on our system-level knowledge and prior EJ studies (Kim et al., 2019; Riley & Gardiner, 2020). The State of South Carolina requires proof of title for dock permits (S.C. Code Ann. §54-13-10), thus a concentration of rental property in a CBG may be correlated with lower abundances of docks.

Objective 1: Structure density mapping

To visualize differences in the distribution of public and private WAI across the landscape, we calculated and mapped the density of WAI for every 100 m grid cell across the 573 CBG study area using the "Point Density" tool in ArcMap. We calculated WAI density values for both a 10 and 1.6 km radius area around each focal cell. Thus, for each cell in the mapped outputs, the density value represents the number of public or private structures within 10 or 1.6 km. We chose these values to represent driving (10 km) and walking (1.6 km) distances. Although these exact distances are arbitrary, we believe they are reasonably representative of the availability of WAI for those with and without a vehicle. Additionally, we calculated the total and percentage land area that contained public or private WAI within driving or walking distance.

Objective 2: Public WAI logistic model

Because piers and public boat landings are commonly built along freshwater rivers and beaches, we used the 283 CBGs of the Beach, Freshwater, and Marsh Zones to model the distribution of public WAI. We fitted a logistic regression using the "glmmTMB" package (Brooks et al., 2017) in R to model the probability a CBG would contain any public WAI. We chose to model public WAI presence/absence because the range of public WAI

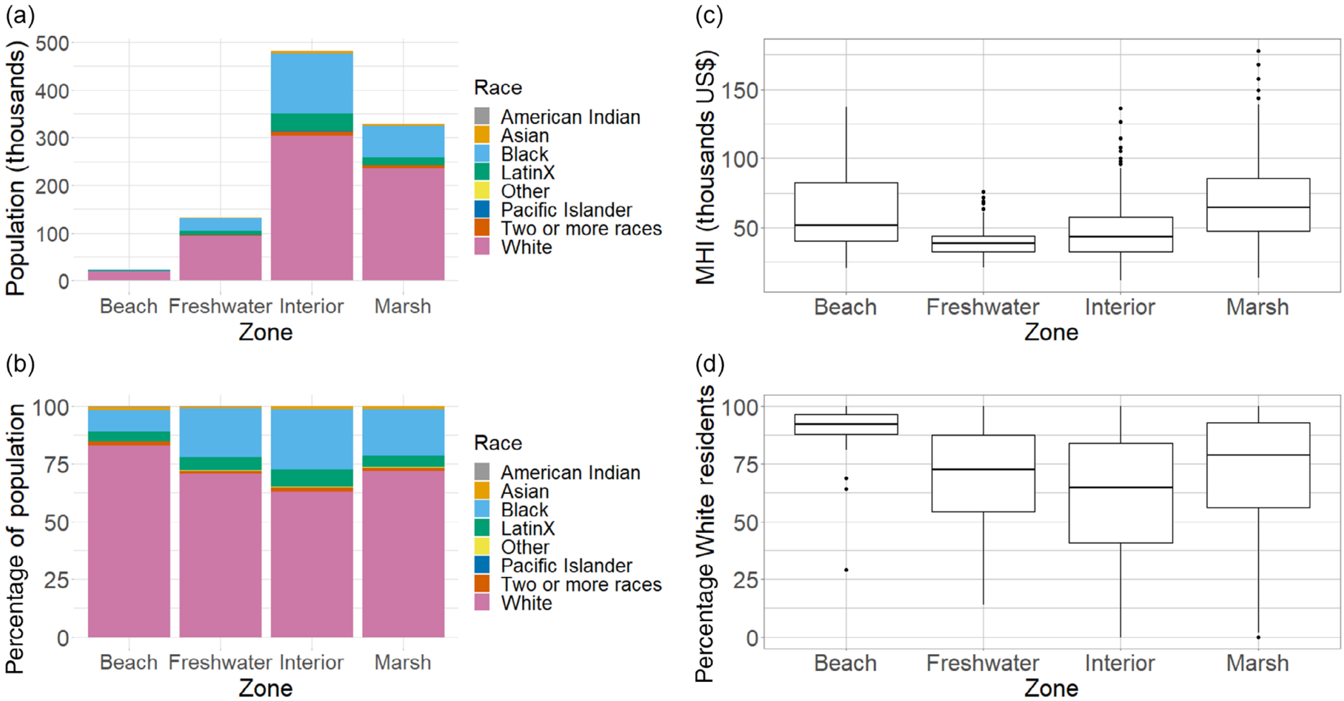

FIGURE 2 Zone-level descriptive statistics for total population in thousands of people (a) and percentage population (b) of American Community Survey-defined racial groups. (c, d) Boxplots of census block groups median household income (MHI) in thousands of dollars and percentage White residents across zones, respectively. The black midline of the boxplot represents the median, box edges represent the 25th and 75th percentiles (interquartile range, IQR), error bars represent 1.5× IQR, and individual points represent outliers outside of the error bar range.

abundance was small (0–4), and we felt that the results of the logistic regression were more readily interpretable. We ran a supplemental analysis on public WAI abundance using a Poisson regression that yielded comparable results. We include this analysis in Appendix S1: Table S2 and Figure S3.

We included a centered median household income variable (in thousands of US$) and percentage White as the predictor variables of interest. Other fixed effects included percentage homeowners in the CBG, centered population of the CBG (in hundreds of people), shore length (in km), and the number of docks in the CBG to account for the potential influence of private WAI abundance on public WAI. We used total population in lieu of population density because CBG land area (the denominator for population density) is highly collinear with shore length. We included county and census tract as random effects to account for the nesting of CBGs within census tracts within counties. We tested and found no support for an interaction between the variables for income and race, so we removed the interaction from the model. We did not find any evidence of multicollinearity of predictor variables (VIF < 2).

We ran similar model diagnostics for Objectives 2–4. We examined residuals for homoscedasticity using the "DHARMa" package (Hartig, 2021) in R. Due to the implicit spatial nature of our data, we analyzed the residuals from our regression to determine whether we needed to explicitly include space in the model. A Moran's I test assuming an inverse-distance weighting relationship on the residuals revealed no significant autocorrelation ($z = -0.31$, $p = 0.75$); therefore, we did not include an explicit spatial covariance structure in this model. We used likelihood ratio tests to examine the significance of individual terms in the model. To assess the strength of significant terms, we calculated and plotted their conditional effects using the "ggeffects" package (Lüdecke, 2018). "ggeffects" generates predicted values for the response variable across the range of a focal predictor variable while holding all other terms in the model constant at their mean values. The *y*-axes of conditional effects plots were back-transformed to the original scale of the data.

Objective 3: Distance to public WAI model

In addition to modeling the probability of public WAI presence, we used distance to the nearest public WAI as a response variable. This approach has been used in other EJ analyses of public water access points (Kim et al., 2019; Montgomery et al., 2015) and has the advantage of providing a more embodied measure of the accessibility of public WAI than simple presence/absence or counts. Because individuals must travel to reach public WAI, travel distances often influence people's willingness and ability to use these public spaces (Montgomery et al., 2015; Morelle et al., 2019). Distance to the nearest public WAI was lognormally distributed and we fitted these data using a linear mixed effects model. We included the same fixed and random effects as in Objective 2 but swapped the length of shoreline with the overall land area (in km^2) as this analysis covers a larger portion of CBG geometry and not just coast-adjacent portions.

We assessed model residuals for normality and homogeneity of variance and a Moran's I test found no evidence of residual spatial autocorrelation ($z = 1.53$, $p = 0.12$). There was no evidence of multicollinearity (VIF < 2). As before, we used likelihood ratio tests to examine significance of model fixed effects and plotted conditional effects using the "ggeffects" package.

Objective 4: Private WAI (dock) model

Unlike our models of public WAI, we only analyzed the 187 block groups in the Saltwater Zone (Figure 1) for our model of dock abundance. We restricted our geographic area because docks cannot be built along beachfront and are uncommon on inland, freshwater rivers (the Saltwater Zone contained 90.8% of the docks across the entire study area). We fitted a zero-inflated, negative binomial mixed model with dock count as the response variable using "glmmTMB." We included the same random and fixed effects as in the public WAI abundance model with two exceptions: (1) we log transformed shore length to meet assumptions of homoscedasticity in model residuals; and (2) we swapped out the fixed effect for total dock count with the abundance of public WAI in the CBG to account for the potential influence of public WAI abundance on private WAI. We again tested and found no support for an interaction between the variables for income and racial composition. We found no evidence of multicollinearity (VIF < 2).

As before, we examined the model residuals for homoscedasticity using the "DHARMa" package and spatial autocorrelation using ArcMap. A Moran's I test revealed significant spatial autocorrelation of model residuals ($z = 2.16$, $p = 0.031$). Residual spatial autocorrelation violates the assumption of observational independence for inferential statistical tests (Ver Hoef et al., 2018) and must be corrected using spatial regression approaches to obtain reliable estimates of significance. We refit the model with a spatial exponential covariance structure (Liu, 2016), which eliminated spatial autocorrelation of the residuals ($z = 0.65$, $p = 0.51$). As with the public WAI models, we used likelihood ratio tests to determine the significance of individual model terms and the "ggeffects" package to calculate conditional effects of race and income. We chose to analyze private WAI abundance instead of density because our count model met regression assumptions better than a similar model that used private WAI density as a response variable.

RESULTS

Descriptive statistics of coastal South Carolina counties

A total of 43 public piers, 124 public boat landings, and 11,953 private docks were present across the entire 573 CBG study area in 2016. Dock abundance varied by county. Charleston County contained the most docks (5888 docks, 49.25% of the total), while Jasper County only contained 204 docks (1.7% of the total). Likewise, Charleston County contained the most public WAI with 41, while Jasper County contained the fewest with 12. Charleston County had the highest density of private WAI (4.67 docks/km of shoreline) while Colleton County had the lowest density of private WAI (0.71 docks/km of shoreline). For public WAI, Horry County had the highest density of structures (0.062 public WAI/km of shoreline), while Beaufort and Charleston counties had the lowest (0.031 public WAI/km of shoreline).

The total population of our 573 CBG study area was 969,129 people, with 482,855 people in the Interior Zone, 329,607 in the Marsh Zone, 133,200 in the Freshwater Zone, and 23,467 in the Beach Zone (Figure 2a). Overall, an estimated 67.5% of the study area population was White, 22.9% was Black, 6.4% was Latinx, 1.1% was Asian, and less than 1% was either American Indian, Pacific Islanders, or another race. When aggregated by Zone, the Beach Zone showed the lowest racial diversity (82.8% White), while the Interior Zone showed the highest racial diversity (Figure 2b). CBGs in the Marsh Zone had a substantially higher median household income (US$64,602) than CBGs in the Freshwater (US $38,512), Interior (US$43,483), and Beach (US$51,740) Zones (Figure 2c). Last, CBGs in the Beach Zone had a higher median percentage White population (92.2%) than the Marsh (78.7%), Freshwater (72.6%), and Interior (64.8%) Zones (Figure 2d).

Objective 1: Structure density mapping

WAI density was highly heterogeneous (Figure 3). Our 573 CBG study region covered a total area of 1,370,664 ha. Of the total area, 1,150,340 ha was within 10 km (driving distance) and 589,068 ha was within 1.6 km (walking distance) of a navigable fresh or saltwater river. For the region within 10 km of water (Figure 3a,b), 953,721 ha (82.9% of land area) contained a private WAI within 10 km and 1,033,531 ha (89.8%) contained a public WAI within 10 km. Public WAI covered a greater land area than private WAI at the 10 km search radius due primarily to the presence of public boat landings along some freshwater rivers in Horry and Georgetown counties. Although the total land area within 10 km of a public WAI was greater than private WAI, the density of these structures was two orders of magnitude larger for private WAI. At walking distance, there was a pronounced difference in the land area within the 1.6 km search radius of a private and public WAI (Figure 3c,d). In total, 356,187 ha (60.4%) contained a private WAI within 1.6 km, while 92,613 ha (15.7%) contained a public WAI.

Objective 2: Public WAI logistic model

The probability of a CBG containing a public WAI decreased with income (Table 1; $\chi^2(1) = 9.76$, $p = 0.0018$), but was unaffected by the White population

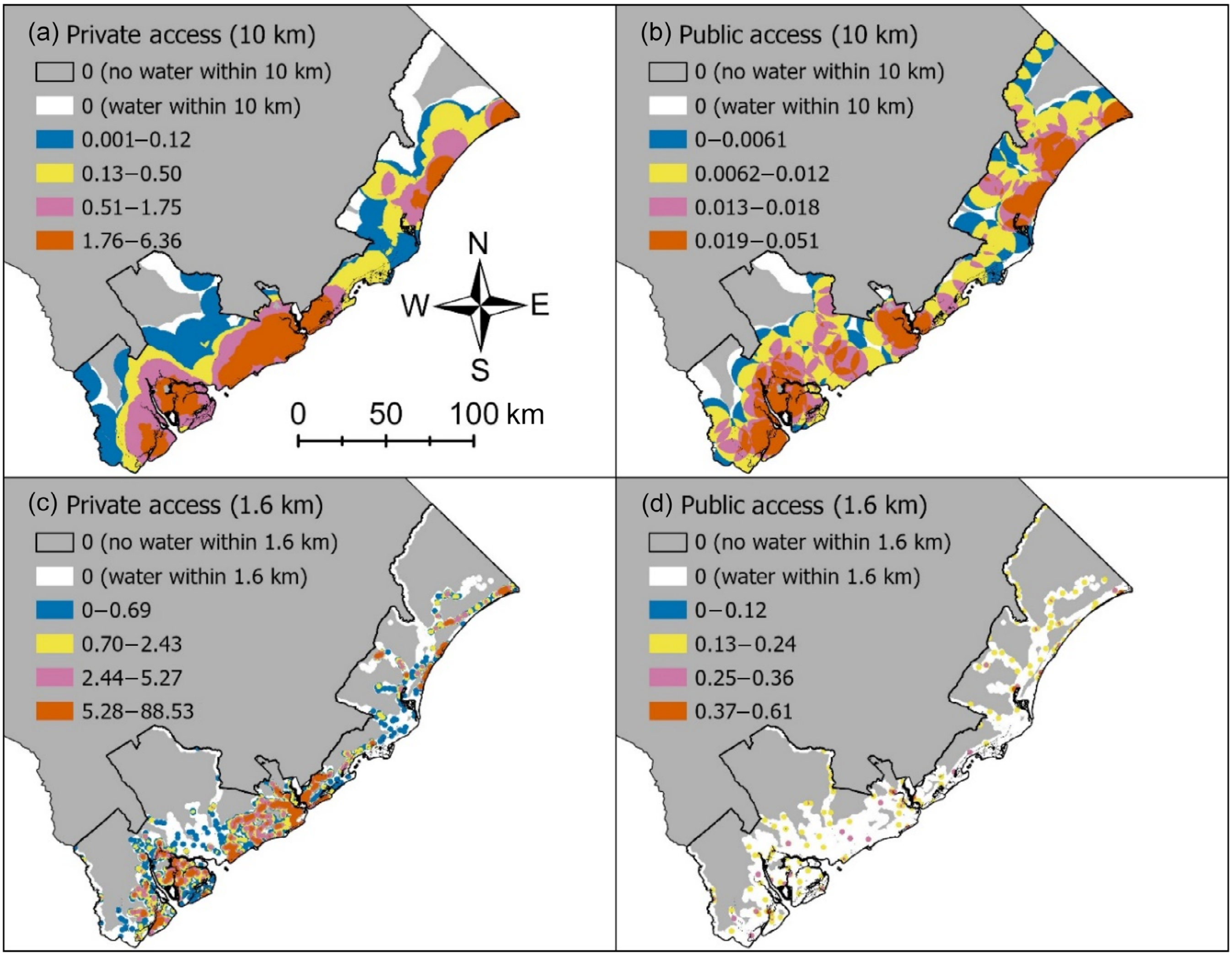

FIGURE 3 Water access infrastructure (WAI) density maps for private (a, c) and public (b, d) WAI across the entire six-county study area. Counties are outlined in black; gray space represents areas with no water or WAI within the search radius; and white represents areas with water, but no WAI within the search radius. The color ramp on the map represents 20% quantiles of density values for WAI and is used across all panels. Note the different scales of density values for private and public access with the same search radii (i.e., a vs. b and c vs. d). Scale 1:2,500,000 for all panels. Distance scale and compass orientation is the same for all panels.

percentage (χ^2 (1) = 0.38, p = 0.53). As expected, the term for shore length was highly significant and positively correlated with public access probability (χ^2 (1) = 11.46, p < 0.001) and the number of docks was borderline significant (χ^2 (1) = 3.67, p = 0.054). Examining the conditional effects, the predicted probability of a CBG containing a public access structure plummeted from 61.2% (95% confidence interval: 44.1%–75.9%) to 2.3% (0.3%–14.3%) from the lowest to highest income CBGs (Figure 4a). As shoreline increased, the likelihood of a CBG containing a public WAI increased from 22.3% (15.7%–30.8%) to 98.7% (69.7%–100%).

Objective 3: Distance to public WAI model

The distance to nearest public WAI model yielded distinct results from the logistic regression of public WAI. Neither income (Table 2; χ^2 (1) = 2.33, p = 0.13)

TABLE 1 Summary of regression output for fixed and random effects for the logistic regression of public water access infrastructure.

	Fixed effects			
Variable	**Untransformed coefficient**	**SE**	**χ^2 value**	***p*-value**
Intercept	−1.8	0.84	…	…
Income (thousands US$)	−0.026	0.0079	9.76	0.0018
% White	−0.0045	0.0071	0.38	0.53
% Homeowner	0.01	0.0092	1.21	0.27
Population (hundreds)	0.0034	0.012	0.07	0.78
Shore length (km)	0.031	0.011	11.46	<0.001
Dock abundance	0.0059	0.0032	3.67	0.054

Note: Random effects as follows: level = variance; county = 1.99×10^{-9}; census tract = 0.28.
Abbreviation: χ^2, chi-squared value from likelihood ratio test.

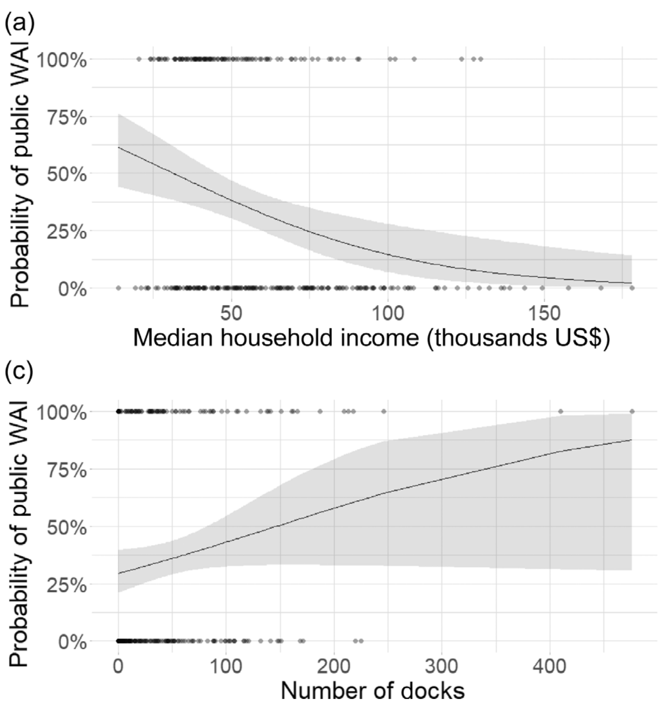

FIGURE 4 Conditional effects plots for income (a), shoreline length (b), and dock abundance (c) in the logistic regression of public water access infrastructure (WAI). Lines represent conditional effects predictions with 95% confidence intervals. Points plot the raw data and darker points indicate overlap of two or more points. Income: χ^2 (1) = 9.76, p = 0.0018; shoreline: χ^2 (1) = 11.46, p < 0.001; dock abundance: χ^2 (1) = 3.67, p = 0.054.

or racial composition (χ^2 (1) = 1.48, $p = 0.22$) showed a significant relationship with public WAI distance. Only land area (χ^2 (1) = 16.61, $p < 0.001$) and total population (χ^2 (1) = 4.82, $p = 0.028$) showed positive correlations with public WAI distance (Figure 5a,b). Our model predicted distance to nearest public access to increase from 4.56 km (4.07–5.10 km) to 13.63 km (8.39–22.15 km) across the range of CBG area in the study. Likewise, as population size increased, the distance to nearest public WAI increased from 4.55 km (3.98–5.22 km) to 7.93 km (5.22–12.04 km).

Objective 4: Private WAI (dock) model

The spatial exponential model of dock count showed a reverse of the trends seen in the public WAI logistic model. Our analysis revealed no effect of income on dock abundance (Table 3; χ^2 (1) = 0.05, $p = 0.82$), but

TABLE 2 Summary of regression output for fixed and random effects for the model of distance to nearest public water access infrastructure.

	Fixed effects			
Variable	**Untransformed coefficient**	**SE**	**χ^2 value**	***p*-value**
Intercept	1.10	0.20	...	...
Income (thousands US$)	0.0025	0.0016	2.33	0.13
% White	−0.0022	0.0019	1.48	0.22
% Homeowner	0.0045	0.0025	3.24	0.072
Population (hundreds)	0.0065	0.0029	4.82	0.028
Land area (km^2)	0.0033	0.00080	16.61	<0.001
Dock abundance	−0.00060	0.00060	0.99	0.32

Note: Random effects as follows: level = variance; county = 2.64×10^{-10}; census tract = 0.28.
Abbreviation: χ^2, chi-squared value from likelihood ratio test.

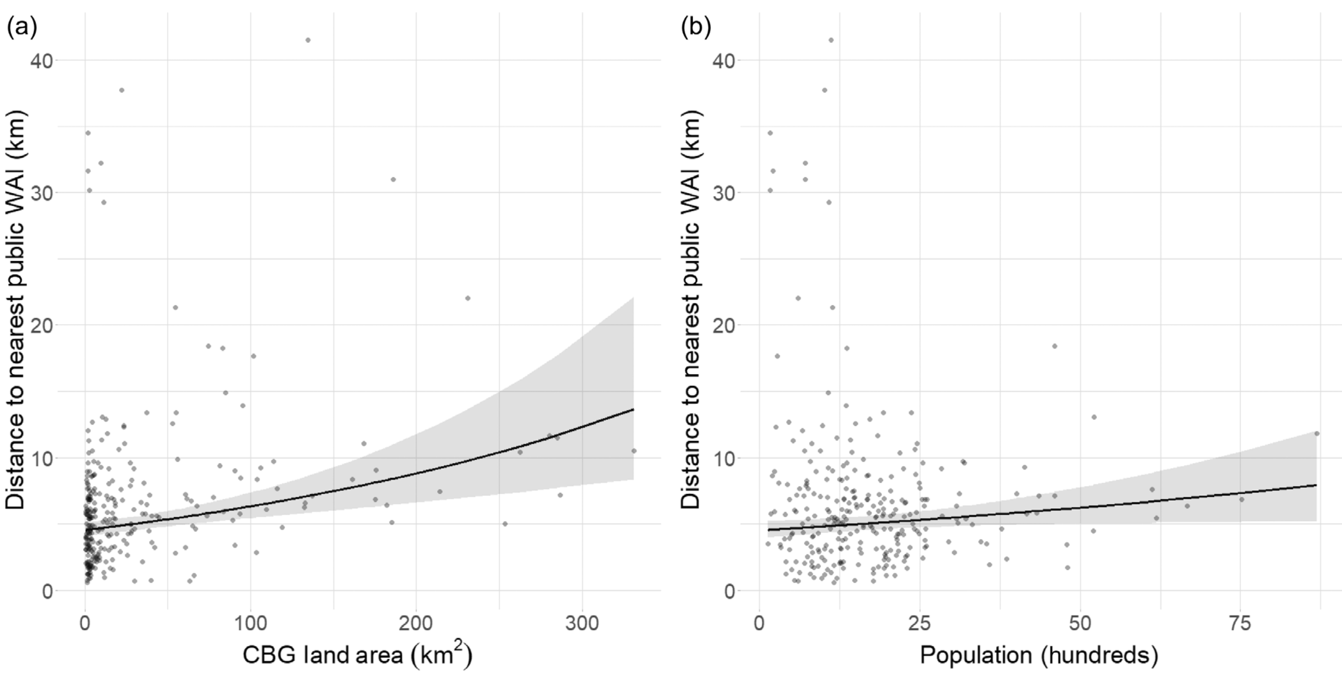

FIGURE 5 Conditional effects plots for census block group (CBG) land area (a) and population size (b) in the model of distance to nearest to public water access infrastructure (WAI). Lines represent conditional effect predictions with 95% confidence intervals. Points plot the raw data and darker points indicate overlap of two or more points. CBG land area: χ^2 (1) = 16.61, $p < 0.001$; total population: χ^2 (1) = 4.82, $p = 0.028$.

did reveal a significant, positive effect of White population percentage (Table 3; χ^2 (1) = 7.61, $p = 0.0058$). Shore length showed a highly significant, positive correlation with dock count (Figure 6b; χ^2 (1) = 42.78, $p < 0.001$), but no other terms were statistically significant. Racial composition demonstrated a strong conditional effect, as the number of docks in a CBG increased from 24 (12–46) to 78 (48–126) docks between CBGs that are 0% and 100% White (Figure 6a). The two large dock outliers did not influence the statistical significance and conditional effects of these variables, as a model rerun without these outliers showed negligible differences.

DISCUSSION

General interpretation of results and methodological considerations

We found that public and private WAI differ in their distribution across the South Carolina coast. The relationship

TABLE 3 Summary of regression output for fixed and random effects for the model of private water access infrastructure abundance.

	Fixed effects			
Variable	Untransformed coefficient	SE	χ^2 value	*p*-value
Intercept	0.79	0.53	…	…
Income (thousands US$)	0.00077	0.0034	0.05	0.82
% White	0.012	0.0042	7.61	0.0058
% Homeowner	0.0098	0.0052	3.49	0.062
Population (hundreds)	0.0045	0.0058	0.61	0.43
Shore length (km)	0.58	0.088	42.78	<0.001
Public access presence	0.27	0.17	2.69	0.10

Note: Random effects as follows: level = variance; county = 7.89×10^{-9}; census tract = 0.049.
Abbreviation: χ^2, chi-squared value from likelihood ratio test.

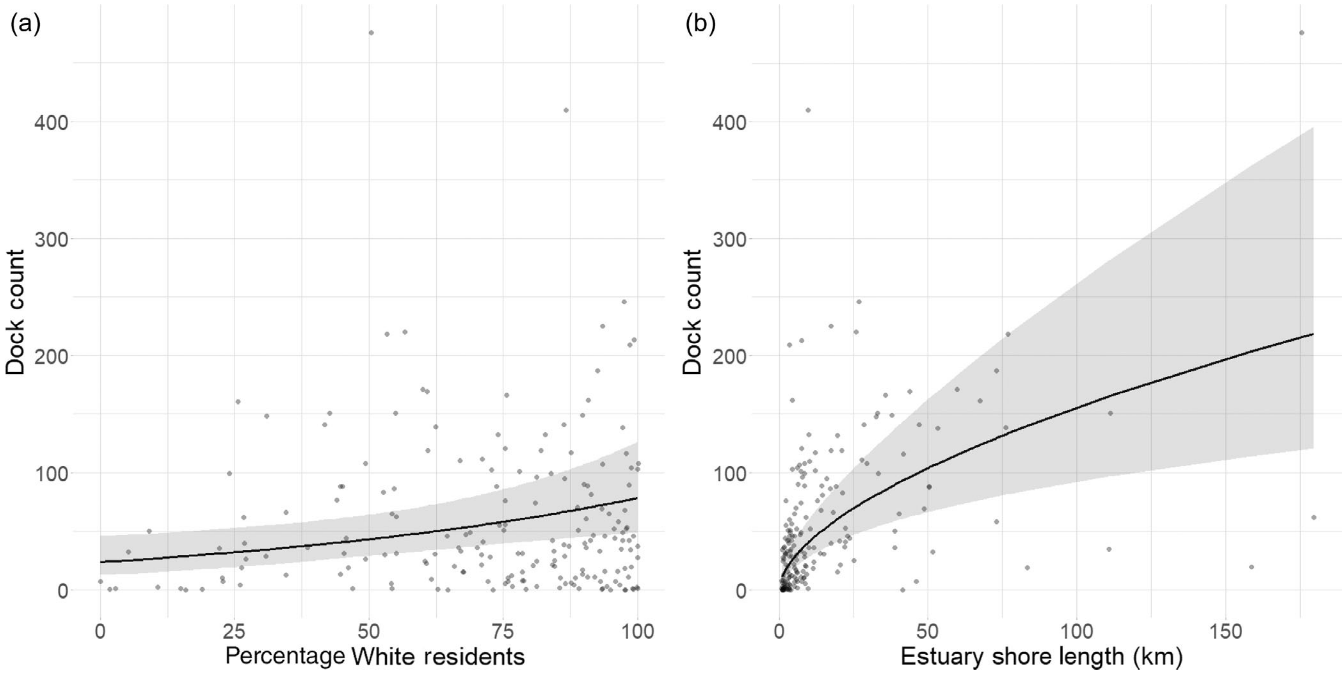

FIGURE 6 Conditional effects plots for percentage White residents (a) and shore length (b) in the model of private dock count. Lines represent conditional effect predictions with 95% confidence interval. Points plot the raw data and darker points indicate overlap of two or more points. Percentage White: χ^2 (1) = 7.61, $p = 0.0058$; shoreline: χ^2 (1) = 42.78, $p < 0.001$.

among public WAI, race, and income was contingent on the metric of public WAI availability used and ran counter to our hypotheses. We found that public infrastructure was more likely to occur in areas with lower household incomes, longer shorelines, and more private WAI. Public WAI presence had no correlation with the racial composition of a CBG. Conversely, the distance to the nearest public WAI showed no relationship with income or racial composition, but increased with the land area and population of CBGs. Private WAI partially conformed to our predictions, as abundance was greater in predominantly White CBGs, while income was not correlated.

The results of the public WAI models suggest that the contemporary distribution of public structures is broadly equal across racial groups and economic classes in these six counties, with an elevated likelihood of public WAI presence in lower income areas (Figure 4a). The divergent results we obtained from both public WAI analyses highlight the importance of evaluating multiple response variables when examining access and being deliberate and transparent in their application (Riley & Gardiner, 2020). We see value in considering the probability of occurrence, the abundance of public WAI (Appendix S1: Figure S3), and distance metrics for public WAI availability and suggest all approaches have utility depending on need and purpose. For example, a city planner may value building additional WAI in areas where they are already present if a large population lives nearby and providing additional structures will alleviate issues like crowding. Alternatively, planners could rely on distance-based information if their goal is to provide a new place of access in an area that is currently far from public WAI.

Our analysis of docks revealed that private WAI are more abundant in areas with proportionately larger White populations. Holding all other variables constant, docks were 3.3 times more abundant in CBGs that were 100% White (Figure 6a). Although docks serve as a conservative proxy for private water access, this finding suggests that Black and Gullah-Geechee residents may have substantially less private access to marshes than White residents. The lack of an income effect on dock abundance is surprising, as docks are expensive structures. Short, modest docks cost a few thousand dollars at a minimum and long docks with amenities like boat lifts can cost tens of thousands of dollars. It is possible that wealthier CBGs had larger average property sizes, which would tend to drive down the number of docks in a CBG even if most individual properties had docks. Unfortunately, we did not have data on average lot size in CBGs. Our infrastructure dataset does not have information on when docks were built, so we could not rule out the possibility that docks in lower income CBGs were older and temporally mismatched with the current economic status of CBGs. This possibility seems unlikely, however, as docks are a valuable property addition that would increase home cost for new buyers. Last, the lack of an income effect at the CBG level may be due to the scalar limitations of large-scale mapping (Mohai et al., 2009). Although CBGs are the smallest spatial scale at which we can collect demographic data on race and income, development patterns are nonrandom and occur at scales below what CBG data can capture. For example, waterfront property can be exceptionally more expensive than adjacent lots that are not on the water, potentially obscuring income effects at the CBG level that are occurring at the household level.

EJ implications and future directions

This study represents one of the few large-scale analyses of the distribution of WAI in either the ecological or EJ literature. We define access as the ability to physically enter the marine environment, specifically focusing on the relative availability of public and private WAI. This is an intentionally narrow definition given the complexity of a topic like access. Other scholars have conceptualized access as "the ability to derive benefit from things" (Ribot & Peluso, 2003), which encompasses a broader suite of activities than simply being able to enter an environment (Schlager & Ostrom, 1992). While entry into an environment is typically a prerequisite to utilize ecosystem services, we are not considering other factors that influence the ability of coastal residents to benefit from those services (Ernstson, 2013; Palma et al., 2012; Sikor et al., 2017). For example, physical barriers such as parking and lack of transportation (Paloniemi et al., 2018) and symbolic barriers such as signage (Palma et al., 2012; Appendix S1: Figure S4) or fear of interactions with law/game enforcement officials (Finney & Potter, 2018) may also prevent individuals from accessing the marine system. Broader conceptualizations of racism rooted in critical social sciences can illuminate patterns of environmental injustice that are difficult to detect through purely quantitative and mapping approaches (Pulido, 2000). We encourage future research into these aspects to better understand the suite of factors that affect marsh access within the coastal southeast.

Given the relative lack of research into the distribution of WAI in this region and the additional dimensions of access our study did not address, we approach making any definitive statements about equity and justice with caution and encourage further research on this topic. However, we believe this research has illuminated important, meaningful patterns in the distribution of WAI that serve as a starting point for assessing equity in marsh access. Several potential equity concepts could be applied to assess the impacts of WAI distribution and actions to ameliorate inequitable access. For example, one set of criteria for determining equity—"need-based" or "compensatory" models—posits that the distribution of access should be enhanced in historically underserved communities to achieve equality in outcomes and meet community needs (Kim et al., 2019, 2021; Smoyer-Tomic et al., 2004). Both metrics used to examine public WAI did not show any correlation to racial composition, but we found that public WAI are two orders of magnitude less abundant than private WAI, which strongly skewed toward the majority White CBGs. This finding raises the question whether the 167 public WAI are enough to meet the needs of the nearly 1 million residents that live in these six coastal counties. In a "need-based" model, future public WAI would need to be concentrated in majority non-White communities to compensate for the lower levels of private WAI. Furthermore, this overall low abundance of public WAI is accentuated by the small and patchy network of land within walking distance of public WAI (Figure 3d), which could limit public access further for those who do not own a car.

Private WAI abundance increased sharply in CBGs with a proportionately larger White population, suggesting that non-White residents do not own as many waterfront parcels as White residents. We suggest that the most likely explanation for the racial imbalance of private WAI is rooted in the history of property ownership along the southeast coast. Following the Civil War, emancipated peoples and their descendants acquired a significant percentage of the private property in this region (Fisher, 1978; Kahrl, 2012b; Rivers, 2007), delivering a measure of autonomy and opportunity within the broader racist structure of the post-Civil War South. Black communities continued to grow and acquire property until the mid-20th century, when the increasing desirability of coastal land and influx of primarily White migrants from other parts of the USA displaced Black and Gullah-Geechee landowners (Goodwine, 2015; Kahrl, 2012a, 2012b; Rivers, 2006). Several exploitative mechanisms have driven the steep decline in Black and Gullah-Geechee land ownership throughout the southeast (Daniel, 2013; Fisher, 1978; Kahrl, 2012a, 2016; Rivers, 2007). In our study area, mechanisms like the instability of ownership due to heirs property (Johnson & Floyd, 2006; Rivers, 2006) and rising property taxes (Dean, 2012; Gullah-Geechee Cultural Heritage Corridor Commission, 2012; Thomas, 1978) have contributed to land loss among Black and Gullah-Geechee residents. Thus, we contend that the current racially uneven distribution of docks is an EJ issue stemming from the racialized nature of historic and modern property ownership. Although we cannot speak directly to the historic aspects of this hypothesis because we only looked at a single point in time, our landscape-scale analysis, coupled with the more localized work of southeastern historians, strongly implicates property dynamics in the modern-day imbalance of private water access. We are currently evaluating this mechanism by examining the distributions of WAI from 1950 to 2010 in relation to historic census data.

Integrating EJ and ecology

Questions centered on EJ are more than purely social issues. Further analyses of the factors that drive WAI placement can help to address ecological questions centered on the dynamics of human-modified aquatic ecosystems. The physical structure of WAI themselves can directly affect ecosystem structure and function. Coastal infrastructure has been shown to alter the composition of benthic invertebrate communities (Bulleri & Chapman, 2010; Connell, 2000; Iveša et al., 2010; Seitz et al., 2006), limit the density and biomass of macrophytes (Alexander & Robinson, 2006; Gladstone & Courtenay, 2014; Shafer, 1999), obstruct the transfer of materials and energy between aquatic and terrestrial ecosystems (Heerhartz et al., 2014), and facilitate the spread of introduced species (Bishop et al., 2017; Glasby et al., 2007; Rodriguez-Rey et al., 2021; Tyrrell & Byers, 2007). As the pace of development in the marine environment increases (Bugnot et al., 2021), ecologists need to incorporate a broader understanding of coastal infrastructure to predict its spread and mitigate undesired effects.

Moreover, who can access and utilize ecosystem services is relevant to ecologists because different groups interact with the environment in unique and meaningful ways (Brown & Toth Jr., 2001; Burger et al., 1999; Hunt & Ditton, 2002). In freshwater systems in both Mississippi (Brown & Toth Jr., 2001) and Texas (Hunt & Ditton, 2002), researchers found differences in the seasonality, frequency, gear used, quantity of catch, and species targeted by Black and White fishers. Differential proximity of WAI to high-quality habitat for seafood species or public harvesting areas could shape harvest strategies, altering impacts on resources. Aside from fishing, other human activities occur at WAI. High concentrations of boating around boat landings, marinas, and ports have been linked to chemical contamination (Guerra-Garcia et al., 2021; Schiff et al., 2007) and noise pollution (Bugnot et al., 2021; Haviland-Howell et al., 2007;

Popper & Hawkins, 2019) that can directly affect the physiology of marine species. The distribution and accessibility of WAI has direct and indirect effects on coastal ecosystems that bridge social justice and environmental concerns.

CONCLUSION

All areas below mean high water are legally codified as public land under South Carolina law, but our analysis of WAI suggests that equitable water access may not be realized in practice. The racial imbalance in the amount of private access to water has important implications for contemporary non-White communities, particularly the Gullah-Geechee. Many popular accounts of the Gullah-Geechee portray them as an historic group; however, the Gullah-Geechee are still prevalent along the coast and deeply connected to coastal ecosystems (Campbell, 2011; Goodwine, 2015). We have shared these findings with Gullah-Geechee and open land preservation advocacy organizations along the South Carolina coast to support their efforts in maintaining and expanding public water access. We note, however, that our work is just a first step, and large-scale mapping analyses cannot be substituted for the lived experiences of Black and Gullah-Geechee fishers. We see these limitations as evidence for the importance of interdisciplinarity in ecological and EJ research. Strategic partnerships with local communities, historians, geographers, and social scientists working at finer-grain spatial scales are needed to understand the social processes that generate environmental injustices and how communities experience and resist them. As ecologists face increasing calls to incorporate a critical analysis of race into our work (Pickett & Grove, 2020; Schell et al., 2020), there are ways to employ familiar methodologies, cultivate relationships with other bodies of knowledge, and develop research programs that advance our understanding of ecology, while contributing to the communities and ecosystems in which we work.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data (Beauvais et al., 2022a) are available in Dryad at https://doi.org/10.5061/dryad.4xgxd259x. Land cover data were downloaded from NOAA's Digital Coast portal (https://coast.noaa.gov/digitalcoast/data/) by selecting the "2016 C-CAP Regional Land Cover" dataset and searching for county names individually ("Beaufort," "Charleston," "Colleton," "Georgetown," "Horry," and "Jasper"). Code (Beauvais et al., 2022b) is available in Zenodo at https://doi.org/10.5281/zenodo.6917387. Additional supplemental information (Beauvais et al., 2022c) is available in Zenodo at https://doi.org/10.5281/zenodo.6917389.

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SUPPORTING INFORMATION

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

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