Balancing Effectiveness and Equity in Sustainable Water Management Transitions: The Case of the Miami-Dade Water and Sewer Department

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Abstract

In response to diverse socio-environmental challenges, urban water utilities in the United States are transitioning to more sustainable management practices, which are often designed to reduce total water consumption. While these practices can effectively maximize the use of limited water supplies, they may simultaneously exacerbate socioeconomic disparities if their implications for equity are not fully considered. This research examines the potential tradeoffs between effectiveness and equity in urban water transitions by analyzing Miami-Dade County's high-efficiency toilet (HET) voluntary rebate program (VRP) as an example of a sustainable water management practice. Using data on HET-VRP participation, water consumption and billing, and socioeconomic indicators, we analyze the relationship between HET-

VRP uptake and benefit distribution among residents. Through parametric and spatial statistical analyses, we find that areas with higher income and education levels have both higher water consumption and more HET-VRP participation, indicating potential program effectiveness. However, lower participation in vulnerable communities raises equity concerns, underscoring the need for targeted outreach and policies that consider distributional impacts. These findings suggest that urban water systems should better incorporate equity considerations in the planning and implementation of water conservation policies intended to promote sustainable water management.

Keywords: Urban Water Systems, Sustainable Management Practices, Policy Instruments, Water Equity

1. Introduction

In the face of growing environmental stressors, ranging from long-term climatic changes to acute extreme events, the importance of implementing more sustainable water management practices is increasingly recognized. For more than two decades, municipalities in the United States have taken policy actions to shift their urban water management system toward greater sustainability (Hornberger et al., 2015; Hess et al., 2017; Garcia et al., 2019), such as by upgrading infrastructure, investing in wastewater reuse, adapting water rate structures, and incentivizing conservation. These practices are commonly designed to effectively reduce municipal water demand (Inman and Jeffrey, 2006; Katz et al., 2016), allowing urban water utilities to stretch limited or variable water supplies further. However, while these practices can effectively maximize the use of limited water supplies, they may simultaneously exacerbate socioeconomic disparities if their implications for equity are not explicitly considered.

Urban water utilities must simultaneously manage several interacting tasks related to water supply sustainability, such as maintaining physical infrastructure (e.g., aging water distribution networks), adapting to environmental changes (e.g., climate change driven aridification), and meeting customer demands, all while working within largely risk-averse political environments characterized by slow-moving institutional governance factors (e.g., resistance to rate increases and water use restrictions). Though equity is commonly partially considered in each of these tasks (e.g., How are the costs of new infrastructure spread among customers?), evidence suggests that local governments in the U.S. and other countries have struggled to prioritize sustainability-related social equity issues alongside other economic, environmental or cost-efficiency goals (Hess and Brown 2018; Opp 2017; Opp et al. 2018; Roberts 2003). For example, local government managed utilities commonly increase the fixed charge component of water rate structures to help stabilize a utility's revenue, thereby promoting more reliable and high-quality service (Porcher, 2014; Luby et al., 2018). However, this change in rate structures can disproportionately impact households that consistently use less water and have, thus, historically paid lower bills based on their actual water consumption (Gerlak et al., 2021). Such an impact exemplifies the importance and understudied tradeoffs related to the mix of policy instruments used in sustainable water management transitions, particularly regarding their effectiveness and equity, that must be better understood to promote truly sustainable urban water management systems (Clark et al., 2022; Farmer, 2022; Jacob and Ekins, 2020).

Overall, utilities must consider the differential impacts that sustainability practices have on diverse socioeconomic groups within a community, in addition to evaluating how effective these practices are at reducing water use to meet sustainability goals (Tong et al., 2021; Olmstead and Stavins, 2009). Accordingly, this study adapts an evaluation framework to analyze both the effectiveness and equity of a water sustainability policy. Guided by this adapted policy framework, we evaluate the effectiveness and equity of a common water conservation policy instrument, voluntary rebate programs (VRPs), in a large U.S. metropolitan area – the City of Miami and surrounding Miami-Dade County – as part of their transition toward sustainability (Treuer et al., 2017). Water utilities commonly use VRPs to incentivize residents living in qualified households to purchase and install high-efficiency technology (e.g., shower heads, faucets, toilets) in exchange for a financial rebate from the utility (Miami-Dade County, 2023; City of Tucson, 2023; El Paso Water, 2019). Our primary objective is to assess both the effectiveness of a VRP at reducing water use and the distributional equity of a VRP in adoption by households across socio-demographic groups to understand the tradeoffs and potential differential impacts of policy instruments used in sustainability transitions. This analysis is therefore guided by the following research question: What does household VRP participation reveal about the tradeoffs between effectiveness and equity in urban water management policy instruments? We draw from extensive data on resident participation in rebate programs, their water consumption and billing, and socioeconomic indicators from Miami-Dade County households over recent years (2019-2023). We employ a variety of spatial and parametric statistical tests to evaluate these data in terms of the effectiveness and equity of the VRP program.

This study provides several theoretical and practical insights. We find that while higher water rebate participation occurred in neighborhoods using or expected to use the most residential water, less rebate participation occurred in neighborhoods with households expected to benefit the most financially from the VRP (e.g., higher poverty-level neighborhoods). This indicates that, as currently implemented, the VRP may be effective but not necessarily equitable and points to potential pathways for more equitable implementation of VRPs and similar practices. Theoretically, the findings advance a useful conceptual framework for systematically evaluating both the effectiveness and equity of practices used by utilities to transition toward sustainable urban water management. By operationalizing this framework through integrating socioeconomic indicators and spatial patterns of VRP participation, we offer a robust method for assessing both the effectiveness and equity of this transition strategy. This methodological innovation creates a roadmap for future research, enabling a more comprehensive understanding of policy instruments and their impact on diverse communities. Practically, the study provides evidence to not only show which types of households participate in the VRP program, but also where they are spatially clustered. Utilizing spatial statistical tools helped identify links between household VRP rebate participation and effectiveness and equity factors, as well as areas that could be targeted for outreach campaigns. Overall, this study's approach and findings add value to local government sustainability literature and for local government water managers and policymakers aiming to balance the effectiveness of water policy instruments and equity in their communities.

2. Conceptual Evaluation Framework

The concept of transitions is leveraged across various scientific disciplines to characterize the evolution or alterations of a system at multiple governance scales, including local and state levels (Loorbach et al., 2017). In the United States, urban water management systems are governed at federal, state, and local levels. However, in the context of drinking water provision, it is predominantly the local governments or municipalities that bear most governance costs associated with managing local water utilities (Greer, 2020). Given this significant responsibility at the local level, there is a growing interest among scholars in understanding the strategies employed at this governance level to transition toward more sustainable urban water management practices (Bush, 2020).

Sustainability, by its very nature, is a dynamic, multidimensional concept contingent on an array of factors, including, but not limited to, governance institutions, population dynamics, and access to resources (Garcia et al., 2019). Building on prior research (e.g., Garcia et al., 2019), this study adopts the following definition of sustainable urban water systems: "the ability for water providers to maintain or improve standards of living without damaging or depleting natural resources for present and future generations" (Treur et al., 2017, p.892). This definition implies that intergenerational equity should be an evaluative criterion but defers to individual communities, users, and providers to determine what system performance might look like (Anderies et al, 2013). Thus, it not only encapsulates the fluid nature of sustainability but also centralizes the role of water providers in determining appropriate metrics for assessing progress. In this study, we focus on transitions toward urban water management sustainability as the overarching area of inquiry.

Water utilities often employ a variety of policy instruments to facilitate their transition toward sustainability. According to Krause et al. (2019), policy instruments serve as "the means by which government policies are carried out" (p. 477). Policymakers deliberately design these instruments to realize their objectives and the communal goals of citizens and interest groups (Feiock, 2018; Krause et al., 2019).

Among these instruments, VRPs emerge as specialized instruments aimed at propelling sustainable practices within utility management by offering financial incentives to consumers for purchasing efficient appliances. Studies indicate VRPs effectively promote energy efficiency among the general population (Howlett, 2019). However, they may disproportionately benefit higher-income households, who have both awareness of these programs and the means to purchase new appliances, potentially exacerbating inequalities (Reames 2016).

To facilitate the systematic evaluation of such local sustainability-based policy instruments, Curley et al. (2020) developed a conceptual framework which posits that the outcomes of policy instrument implementation are intrinsically tied to a community's demographic composition. We draw on two of their framework's evaluative criteria, including "effectiveness in achieving program goals" and "reduction of inequalities in outcomes and burdens" (Curley, et al., 2022, p. 538). They developed this framework within the context of an energy VRP, which offered the City of Tallahassee Utility's customers $40 to $300 rebates for purchasing new Energy Star-certified technology to reduce household energy demand. The study found that household energy consumption rates were not associated with VRP adoption and that predominantly white and highly educated households were associated with higher VRP participation, suggesting that the VRP was neither effective nor equitable.

The Curley et al. (2020) framework provides a useful conceptual tool for systematically evaluating similar policy instrument outcomes in different contexts, such as that of urban water. In this study, we adapt the framework to assess the effectiveness and equity of the water-based VRP policy instrument implemented in Miami-Dade County in 2007. Specifically, we use their definition of 'effectiveness' as the degree to which the policy instrument fulfills its overarching goal (i.e., water conservation). Additionally, we follow their understanding of 'equity' as the extent to which the policy instrument alleviates inequalities. In the context of our study, the reduction of inequality would imply the reduction of financial water costs for households with limited resource access. This is gauged through the participation rates of historically vulnerable and low-income communities in a High-Efficiency Toilet (HET) VRP (HET-VRP). Access to this program offers potential financial incentives that can relieve the water cost burden for these vulnerable communities. This approach guides the hypotheses of our study, which are tailored to the Miami-Dade HET-VRP.

2.1. Hypotheses

Multiple community-level spatial analyses show that socio-demographic factors and household factors exist in spatial patterns and have linked these patterns to household water usage at the community level (e.g., House-Peters et al., 2010). Socio-demographics and household types commonly form spatial clusters within metropolitan regions, suggesting a correlation between water usage determinants and urban spatial structure (Avni et al., 2015). Consequently, it is essential to assess the connection between VRP participation and household types from a spatial perspective, particularly when analyzing local communities. By examining the spatial link in VRP participation, we can identify the types of people and households to target in future VRP campaigns and the areas where these campaigns would be most effective, thus making this approach theoretically and practically beneficial (Barnes et al., 2021).

Policy instruments, such as VRPs, are typically chosen for their anticipated effectiveness in achieving multiple dimensions of policy objectives, which can vary based on local goals (Olmstead and Stavins 2009). In the context of transitions toward sustainability, an effective policy instrument could serve various purposes. In the case of water conservation, effective VRP participation would ideally involve households that consume, or are expected to consume, large volumes of water. Such targeting aligns with determinants of increased water demand, as identified in existing literature, including socio-demographic factors like family size, household income, and education, as well as household factors like ownership status, age of home, and type of residence (Chang et al., 2010; Cominola et al., 2023). Given the effectiveness expectations and possible spatial water consumption clusters, we test the following hypothesis:

- H1: Households in neighborhoods (i.e., census tracts) with higher household water demand are more likely to participate in the VRP.

Second, though the core purpose of VRPs traditionally focuses on water conservation for environmental sustainability, increasing attention is being given to how such policy instruments could also help reduce inequality (Curley et al., 2020). Policy instruments in sectors such as energy have evolved to target both energy conservation and social empowerment (Johnson et al., 2018), and similarly, VRPs in the water sector are now being scrutinized for their capacity to mitigate social disparities, specifically household water cost burden. The 'water cost burden' is commonly defined as the percentage of household income allocated to water services, representing a crucial metric of affordability. This financial strain disproportionately impacts low-income and vulnerable households, which are characterized by limited financial resources and heightened socio-economic risks (Mack and Wrase, 2017; Teodoro and Saywitz, 2020; Pierce et al., 2021; Goddard et al., 2022). Consequently, the potential for VRPs to mitigate these disparities must be rigorously evaluated.

In our study context, we define reduced inequality as vulnerable household participation in the VRP. Participation in VRP can mitigate inequalities as the HET rebate provides short-term and long-term financial benefits. These include an immediate financial rebate upon installing a HET and ongoing savings due to reduced water costs with each flush.

Our emphasis on this aspect is particularly significant because VRPs are structured to be more inclusive than other resource-saving initiatives. For example, energy loan and rebate programs often require upfront payments or proof of financial credibility, creating barriers for minority and low-income households (Pivo, 2014). In contrast, VRPs may offer immediate financial relief without necessitating large initial investments, lowering program access barriers. Yet, this pursuit of inclusivity raises a dilemma: traditional VRPs are most ‘effective’ when targeting the highest water consumers for maximum conservation, a demographic that might not necessarily overlap with the financially burdened households that would benefit the most from the program’s financial incentives. Given the recognized tension between effectiveness in water conservation and social equity, our study aims to examine this dynamic. We therefore test a second hypothesis that deals with the equity aspect of VRP:

- H2: Households in neighborhoods (i.e., census tracts) with higher water cost burdens are less likely to participate in the VRP.

2.2. Case Study: Miami-Dade Water and Sewer Department (WASD)

The Miami-Dade Water and Sewer Department (WASD) serves as an exemplary case to investigate our research questions due to Miami-Dade county's diverse socioeconomic landscape, ongoing water management transition, and environmental context. In recent decades, WASD has experienced significant water system transitions and implemented effective conservation programs. WASD arguably embarked on its journey towards sustainability in the early 1990s in response to a host of challenges, including rapid population growth, environmental issues, and infrastructure constraints. In 2007, this transition was formalized as WASD launched their Water Use Efficiency Plan (Treuer et al., 2017; Miami-Dade County, 2023). Central to this plan were rebate programs, which incentivized residents to replace less efficient appliances and systems with high-efficiency models, including replacing older, less water-efficient toilets with high-efficiency models in exchange for a financial rebate from WASD. Despite acute water shortages, enduring drought conditions, and economic repercussions of the Great Recession (2007 to 2011), WASD remained committed to its Water Use Efficiency Plan and has consistently successfully reduced the county's overall water demand.

While our analysis concentrates on the effectiveness and equity of a specific conservation instrument, this is one part of a broader transition at WASD that has generally yielded positive financial and operational outcomes. There was a rise in total operating revenues and expenses, demonstrating growth in the utility's earnings and operational costs. Additionally, an upturn in the operating ratio signaled improved operational efficiency. Despite mixed trends in water loss, non-revenue water, and the frequency of water main breaks, a generally positive direction was noted in financial obligations, depreciation of assets, the net position, and investment in capital assets of the utility. Significantly, the period from 2015 to 2021 saw a considerable expansion of capital assets, particularly related to ongoing construction projects, indicating proactive infrastructure development. While the pace of annual water savings has slowed recently, the overall trend points towards the successful implementation of conservation strategies. These initiatives resulted in a substantial reduction in the city's water demand by 2020 (114 gallons per capita per day), as compared to the 2006 levels (153 gallons per capita per day).

Our study narrows its focus on one component of WASD's transition to sustainable water management by evaluating the effectiveness and equity of a key water conservation policy instrument implemented in this water system's community. Specifically, we analyze the HET-VRP and assess how this policy impacts both high water-using and financially vulnerable neighborhoods in the City of Miami and the greater Miami-Dade county.

3. Data and Methods

3.1. Dependent Variable Measure

Miami-Dade WASD provided household HET-VRP participation records for the entire county from 6/01/2019 to 1/01/2023 for both single-family (SFR) and multi-family residences. This dataset includes the household address and the date they received a HET rebate. Only homes built before 1996 are eligible for the VRP rebate. In this study, the dependent variable was measured as the number of households receiving a HET rebate between June 2019 and January 2023, normalized by the total number of eligible homes (built before 1996), expressed as a percentage at the census tract level. We used a linear estimation procedure to estimate the number of these homes based on data from the 2021 American Community Survey (ACS, 2021) five-year estimates, which provided the estimated number of houses built in each decade. We refer to the dependent variable measure as *HET*%. Our unit of analysis is the census tract, chosen over block groups due to superior ACS data reliability at the tract-level, especially when dealing with smaller population subsets such as those in poverty or racial minority groups (Spielman, et al., 2014).

3.2. Direct and Proxy Independent Measures of Effectiveness and Equity

Due to limited household water use and billing data availability, a two-part analysis was conducted at the city and county-levels (Fig. 1). The Miami-Dade WASD provided detailed water use and billing records for approximately 64,000 residential customers in the City of Miami, covering the period from 2018 through 2021. These records allowed for direct measurement of *effectiveness* (i.e., household water demand) and *equity* (i.e., household water cost burden) at the city level. However, due to the low number of census tracts in the City of Miami (134 tracts), statistical tests on this sample may not robustly detect significant associations between high-efficiency toilet (HET) adoption percentages (*HET%*) and the effectiveness and equity measures.

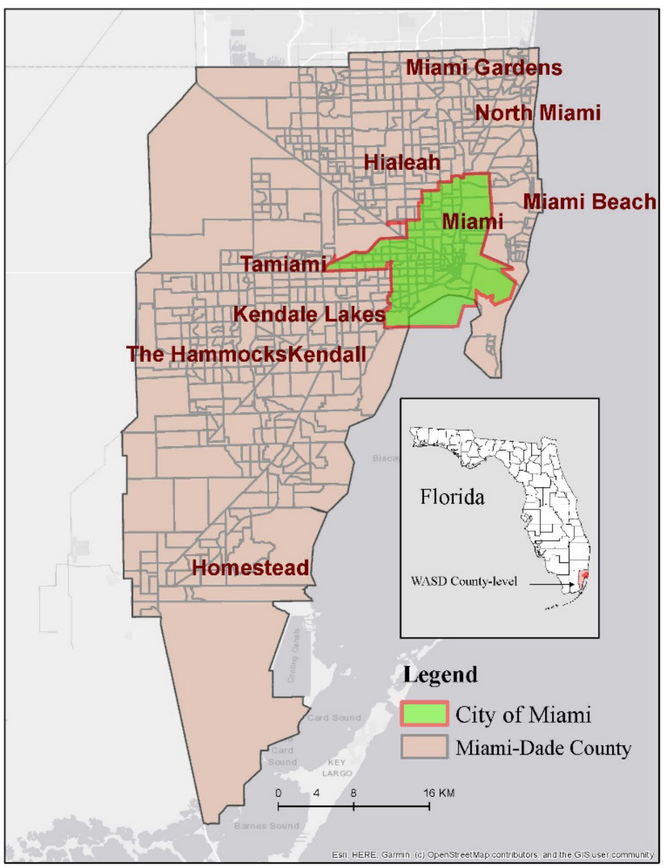

Fig. 1. Miami-Dade County (area outlined in blue) and the City of Miami (area outlined in red) census tract areas included in this study.

To augment and validate the city-level analysis and ensure broader regional applicability, we extended our boundary of study to include the entire county, which encompasses 695 census tracts. For the county-level analysis, we lacked specific household water use and billing data and thus relied on proxy measures (discussed below) to evaluate the effectiveness and equity of HET-VRP participation. These proxy measures, aimed at identifying households 'expected' to have high consumption and a higher water cost burden, are derived from socio-economic and demographic data. To facilitate a comprehensive comparison across the city-level and county-level analyses, these proxy measures were also incorporated into the city-level analysis (Table 1). The data for the proxy measures were sourced from the US Census Bureau's 2021 American Community Survey (ACS) five-year estimates. This two-part analysis is expected to provide a robust and reliable assessment of the WASD HET-VRP policy instrument.

Table 1.Overview of direct and proxy measures for evaluating effectiveness and equity at city and county levels

Level of Analysis	Dependent Variable	Independent Variables		
		Measure Type	Effectiveness Measures	Equity Measures
City Level	Percent of households received High Efficiency Toilet Rebate (HET %)	Direct Measures	• Average gallon water usage per household per day (GPHD)	• Water Affordability Index (average monthly water bill / median household income) • Average water and wastewater bill per household per day (BPHD)
		Proxy Measures	• Median Income • College Education Percentage (College%), • Average Household Size • Single-Family Residences Percentage (SFR%) • Percentage of homes qualified for HET rebate (Qualified%)	• Poverty Percentage (Poverty%) • Racial Demographics (White% AA/Black%, Hispanic%) • Percentage of Rented Households (Rent%)
County Level	Percent of households received High Efficiency Toilet rebate (HET %)	Proxy Measures	• Median Income • College Education Percentage (College%) • Average Household Size • Single-Family Residences Percentage (SFR%) • Percentage of homes qualified for HET rebate (Qualified%)	• Poverty Percentage (Poverty%) • Racial Demographics (White%, AA/Black%, Hispanic%) • Percentage of Rented Households (Rent%)

3.2.1. Direct Measures at the City Level

We use direct household water demand-related measures to *evaluate effectiveness* and *equity* at the city level. For *effectiveness*, we calculated the average gallon of water usage per household per day within each census tract, referred to as *GPHD*, using the household water use records from 2018 to 2021. This direct measure helps identify neighborhoods with high household water consumption. For *equity*, the direct measure involves calculating the Water Affordability Index (Teodoro and Saywitz, 2020), which is the average monthly water bill divided by the neighborhood's median monthly household income (ACS estimates), scaled by 100. A lower value in this index signifies higher water affordability, while a higher value indicates less affordability. We also consider the average water and wastewater bill per household per day using the same billing records (*BPHD*). These direct measures offer a precise assessment of water use and cost burden at the city level.

3.2.2. Proxy Measures for Both City and County Levels

We identified suitable proxy measures for the *effectiveness evaluation* using water demand literature and sourcing the necessary data from the ACS five-year estimates. Research indicates that parameters such as income (Gregory and Di Leo, 2003; Russell and Fielding, 2010; Rachunok and Fletcher, 2023), education (Addo et al., 2018), and household size (Wentz and Gober, 2007; Schleich and Hillenbrand, 2009) positively associate with household water demand. Moreover, household type can be a determining factor (Domene and Saurı´, 2007); for instance, single-family households often have higher water usage rates (House-Peters et al., 2010). Additionally, the year a household was built also impacts water consumption; newer homes often use less water due to water-saving technologies (Guhathakurta and Gober, 2007; Kenney et al., 2008; Caminola et al., 2023). Given previous water demand findings, the following proxy measures are used in the effectiveness evaluation: median income (Median Income), percentage of individuals with a college degree (College%), average household family size (Household Size), percentage of homes that are single-family residences (SFR%), and the percentage of homes eligible to receive a HET rebate (Qualified%).

For the *equity evaluation*, we utilize proxy equity measures focused on wealth and race following the equity evaluation in Curley et al. (2020), which are associated with the water cost burden. These measures include the percentage of individuals in poverty (Poverty%), racial demographics (percent of white non-Hispanic residents (White%), percent African American or Black residents (AA/Black%), percent of Hispanic residents (Hispanic%), and the percent of households that are rented (Rent%).

3.3. Statistical Methods

We constructed a cross-sectional database, aggregated at the census tract level, to conduct both parametric and spatial statistics. Four sets of tests were conducted at the city-level and again at the county-level. We employed (1) Pearson correlation tests (Cohen et al., 2013), (2) Global Moran's I spatial autocorrelation statistics (Odland, 1988), (3) Local Moran's I spatial autocorrelations (LISA) spatial statistics (Anselin, 1995), and (4) Co-location join count spatial statistics (Huang et al., 2004). Pearson correlation tests were executed in STATA and all spatial statistics were generated using the open-source GIS software GeoDa version 1.2 (Anselin, 2021). For all spatial statistics, the Queen contiguity spatial matrix (Grubesic, 2008) was utilized to define a "neighbor" among the census tracts in this study. In this context, any census tracts that share at least one node (i.e., census tract boundaries touch) are considered neighbors. Additionally, we utilized the Census Bureau Tiger/Line census tract shapefile for Miami-Dade County for the spatial tests.

First, Pearson correlations were used to identify associations between the study variables without considering their spatial proximity. Second, the Global Moran's I spatial autocorrelation was used to assess if there is a systematic spatial pattern of similarity (positive autocorrelation) or dissimilarity (negative autocorrelation) among neighboring census tracts. Third, the LISA statistic, an extension of the Global Moran's I test, was used to identify significant clusters or hotspots (e.g., high-income neighborhoods clustering together) and spatial outliers (see Appendix Table A1 for full LISA map result interpretations). Fourth, co-location join count tests were used to examine the degree of co-location associations between the dependent variable and the independent measures (Anselin and Li, 2019). This test can only be used for binary measures. Therefore, for the purpose of the co-location join count tests, all variables were recoded into a binary format. If a census tract had a variable measure value greater than the overall average, it was coded as one; otherwise, it was coded as zero. For instance, a census tract with a higher-than-average HET% value was coded as one, and the census tracts with average or less than average HET% were coded as zero. This analytical approach is valuable as it identifies census tracts or clusters of census tracts that have both a high HET% distribution and a high level of an independent measure (e.g., high water demand, high income, high percentage of college graduates, high percentage of individuals in poverty, etc.).

4. Results

Our study reveals that neighborhoods with high water demand are actively engaged in the HET-VRPs, but economically burdened and ethnically diverse communities are notably underrepresented. This situation exposes a potential tension within the program's objectives—it excels at targeting high-consumption areas but might not be fulfilling other potential objectives, such as reaching communities that could most benefit from its financial incentives. In the sections that follow, we go into greater detail about our results.

4.1. City-level Results

The city level analysis was conducted for 14 measures (both direct and proxy measures) across 134 observations measured at the census tract level. The descriptive statistics shows (Table A2) that HET% ranges from 0 to 3.03%, showing that overall, a small percentage of qualified households participated in the HET-VRP between June 2019 and January 2020.

Fig. 2 provides the city-level Pearson correlation heatmap results. These results show a significant positive correlation between the dependent variable HET% and both SFR% and Qualified%. Not only are these correlations significant, but their correlation coefficients are also at or near 0.3, indicating a strong relationship. Interestingly, these parametric tests do not show a significant association between HET% and the direct effectiveness and equity measures (i.e., GPHD, Affordability Index, BPHD); however, the direct measures do associate with the proxy measures in expected ways (e.g., GPHD positively associates with

Median Income and college, Affordability Index positively associates with Poverty, AA/Black%, and Rent%).

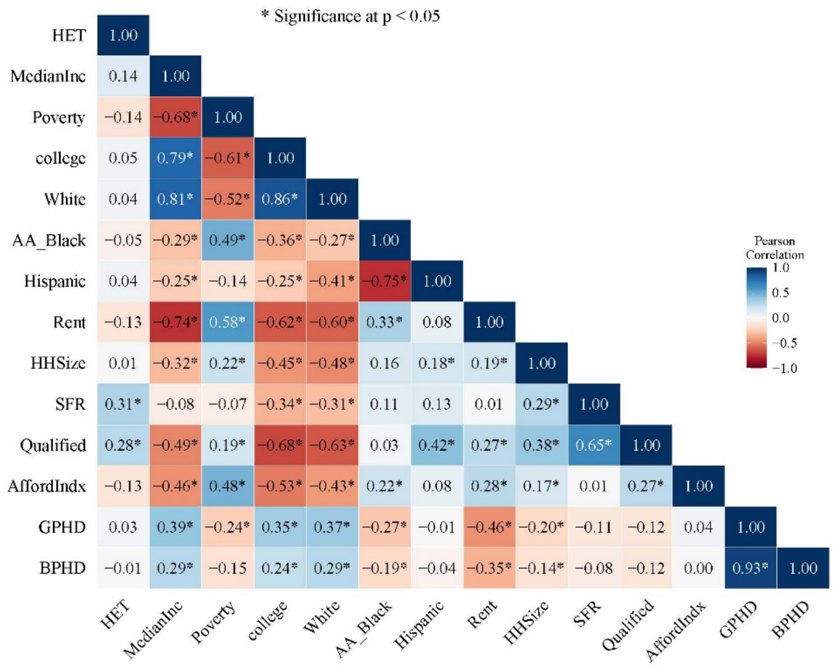

Fig. 2. Pairwise correlations of city-level measures

Table 2 provides the Global Moran's I statistics. All variable measures are significantly positively autocorrelated. The HET% demonstrated a lower degree of spatial autocorrelation than almost all the independent measures, except for Household Size and GPHD. The most significant takeaway from Table 2 is that nearly all variable measures occur in spatially significant clusters in the city, validating the use of and focus on spatial statistics in the city-level analysis.

Table 2. Global spatial autocorrelation results (Moran's I statistics) of city-level measures

Variable Measures	Moran's I Statistic	E[I]	Mean	z-value	permutations	Pseudo p-value
HET%	0.2511	-0.0075	-0.0100	5.454	999	0.001
Median Income	0.5085	-0.0075	-0.0098	10.6922	999	0.001
Poverty%	0.4449	-0.0075	-0.0083	9.0418	999	0.001
College%	0.7565	-0.0075	-0.0086	14.9136	999	0.001
White%	0.6097	-0.0075	-0.0112	12.6775	999	0.001
AA/Black%	0.7643	-0.0075	-0.0076	15.0549	999	0.001
Hispanic%	0.7863	-0.0075	-0.0079	15.6294	999	0.001
Rent%	0.3138	-0.0075	-0.0087	6.4103	999	0.001
Household Size	0.2003	-0.0075	-0.0075	4.0323	999	0.001
SFR%	0.5905	-0.0075	-0.0078	11.6358	999	0.001
Qualified%	0.6603	-0.0075	-0.0079	13.0991	999	0.001
Affordability Index	0.2376	-0.0075	-0.0082	4.9493	999	0.001
GPHD	0.2299	-0.0075	-0.0071	4.9107	999	0.001
BPHD	0.0908	-0.0075	-0.0059	2.0122	999	0.024

Fig. 3 provides the visual LISA univariate results (see Table A3 for the number of LISA significant and insignificant census tracts at the city-level). The High-High results for HET% suggest the emergence of seven hotspots in the city concentrated in the city's south-eastern region. The 26 HET% coldspots, in contrast, are more dispersed across the city, predominantly appearing in northeastern and western regions. Focusing on the overlap with HET% hotspots, it is observed that Median Income, College%, White%, and GPHD demonstrate the most substantial visual overlap, especially in the city's south-eastern region. Similarly, Poverty% and Rent% coldspots visually indicate there is overlap with multiple HET% hotspots within the same south-eastern area. The most notable takeaway from this LISA analysis is that there are visible overlaps in HET% hotspots and the independent measures, validating the use of co-location join count tests to probe the bivariate spatial links between the dependent and independent measures in the next step of this analysis.

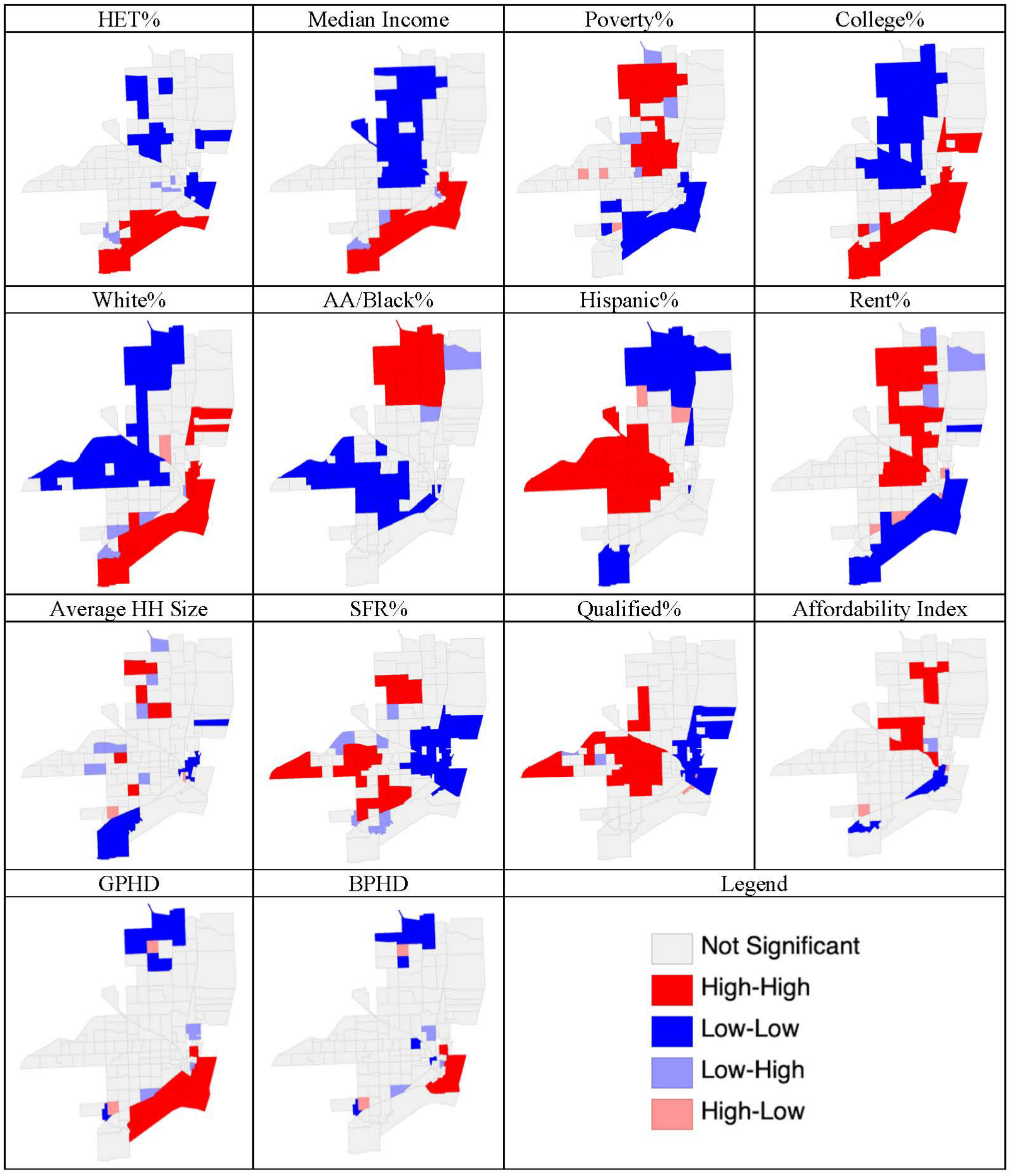

Fig. 3. Local Moran's I cluster results for city-level measures.

Fig. 4 provides the visual city-level binary co-location join count results, which underscore several relevant trends (see Table A4 for the number of significant and insignificant co-location join count tracts at the city-level). The county-level binary co-location join count results are depicted in green if they are significant at the 0.05 significance level or lower. This analysis reveals two key trends in HET-VRP participation in Miami. First, neighborhoods with higher-income households and higher percentages of white residents are more likely to participate in the HET-VRP. These demographic factors appear to be the most significant drivers of program participation. Second, areas with higher water consumption rates—directly measured as Gallons Per Household per Day (GPHD) or indirectly indicated through factors like income, education, and the age of the household structure (Qualified%)—also show higher participation levels. However, these findings come with caveats. The key takeaway from Fig. 4 is that our city-level analysis reveals a striking positive link between effectiveness measures and HET-VRP participation and a negative link between equity factors and HET-VRP participation. However, the low number of significant clusters and the limited number of census tracts available for the city-level analysis suggest that the results from the city analysis should be interpreted cautiously and in conjunction with county results in the next section.

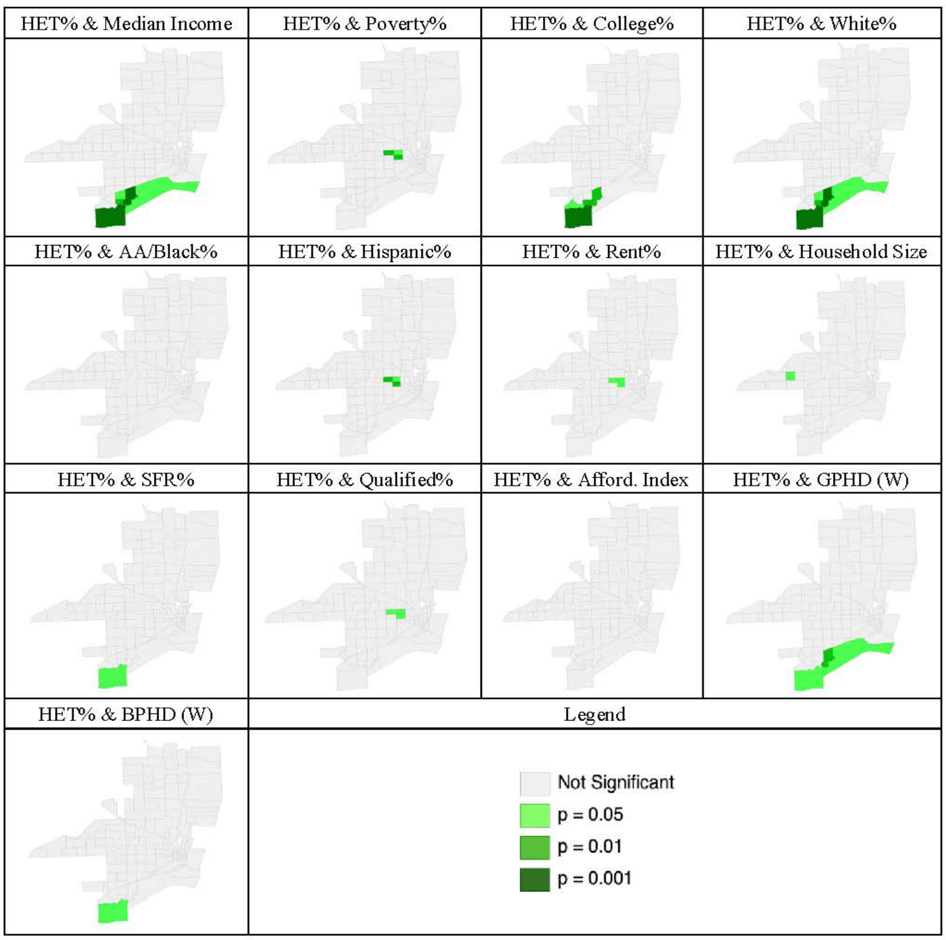

Fig. 4. Local Moran's I cluster results for city-level measures.

4.2. County-level Results

WASD only made water use and billing data available for the City of Miami. As mentioned, due to the low number of census tracts in the city analysis, the city-level statistical tests and subsequent results may not be generalizable (i.e., small sample size bias), necessitating a county-level analysis, using only proxy measures to validate results identified in the city analysis.

The county level analysis was conducted for 11 measures (proxy measures only) across 695 observations measured at the census tract level. Twelve tracts were removed that could introduce bias—those with a low population and zero residential household estimates. The descriptive statistics shows (Table A5) that HET% ranges from 0 to 6.68%, indicating that overall, a small percentage of qualified households participated in the HET-VRP during the period between June 2019 and January 2020, but participation was relatively higher in neighborhoods outside of the City of Miami (city-level HET% ranged from 0-3.03%).

Fig. 5 provides the county-level Pearson correlation heatmap results. Notably, these results show a significant positive correlation between the dependent variable HET% and Median Income, College%, White%, Hispanic% (despite a small coefficient), SFR%, and Qualified%. On the other hand, HET% negatively correlates with Poverty%, AA/Black%, Rent%, and Household Size. The key takeaway from Fig. 5 is that nearly all proxy effectiveness measures (i.e., higher demand neighborhoods) and proxy equity measures (i.e., neighborhoods with higher water cost burden) are associated with HET% in the directions hypothesized (i.e., positive or negative). We note that Hispanic% minorly positively associates with HET% (i.e., opposite of theoretical expectations), but given the particularly large Hispanic community in Miami-Dade, it is possible that the Hispanic% metric is a less reliable equity factor in this community. This finding highlights that communities are different; thus, evaluation must be tailored to the community in question.

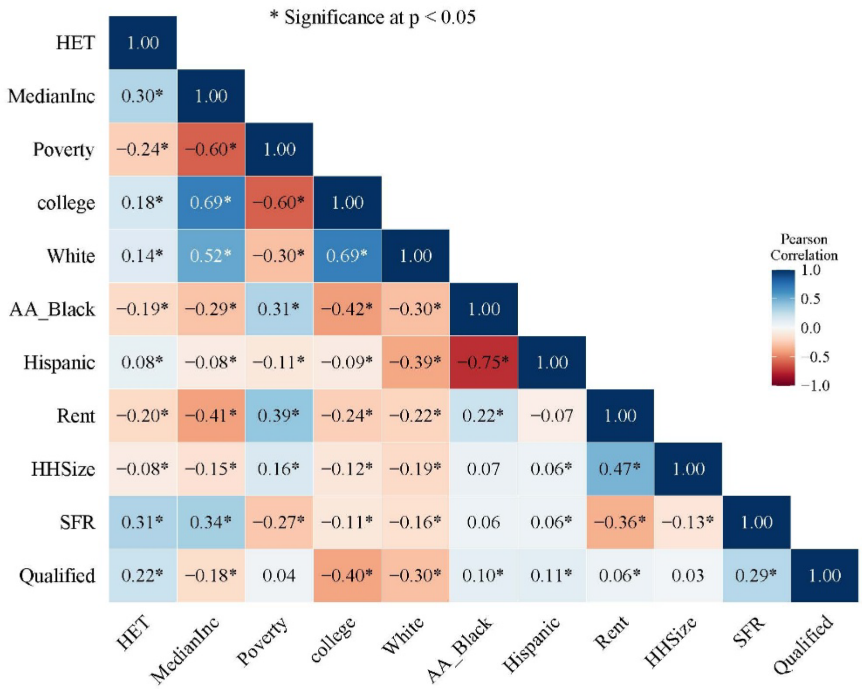

Fig. 5. Pairwise correlations of county-level measures

The results from the univariate Global Moran's I statistics (Table 3) show that all variable measures at the county-level exhibit significant positive autocorrelations. This indicates that each measure exhibits significant spatial clustering (i.e., spatial autocorrelation). The key takeaway from Table 3 is that all variable measures are significantly spatially clustered across the county, validating the use of and focus on spatial statistics in the county-level analysis.

Table 3. Global spatial autocorrelation results (Moran's I statistics) of county-level measures

Variable Measures	Moran's I Statistic	E[I]	Mean	z-value	permutations	Pseudo p-value
HET%	0.2528	-0.0014	-0.0014	11.4556	999	0.001
Median Income	0.4761	-0.0014	-0.0018	22.8260	999	0.001
Poverty%	0.3280	-0.0014	-0.0016	15.2001	999	0.001
College%	0.6873	-0.0014	-0.0019	31.5523	999	0.001
White%	0.6728	-0.0014	-0.0024	29.7278	999	0.001
AA/Black%	0.7941	-0.0014	-0.0013	36.9010	999	0.001
Hispanic%	0.7964	-0.0014	-0.0022	36.7247	999	0.001
Rent%	0.2901	-0.0014	-0.0016	13.6268	999	0.001
Household Size	0.1311	-0.0014	-0.0025	6.0955	999	0.001
SFR%	0.5282	-0.0014	-0.0005	24.3557	999	0.001
Qualified%	0.5636	-0.0014	-0.0005	25.8867	999	0.001

Fig. 6 provides the visual county-level LISA results (see Table A6 for the number of significant and insignificant LISA census tracts at the county-level). The High-High results for HET% suggest the emergence of 70 hotspots in the county (Table A6). Most are concentrated in the mid-eastern portion of the county. This area includes multiple cities, smaller in population than Miami, and south of Miami. The 105 HET% coldspots are more broadly distributed across the county, with many appearing in the northwestern part of the county near the City of Miami and other northwestern cities. Focusing on the overlap with HET% hotspots, it can be observed that Median Income and College% also exhibit a large grouping of hotspots in the mid-eastern region of the county. White%, Household Size, and Qualified% also visibly indicate there is some overlap in HET% hotspot areas. In contrast, HET% coldspots, Median Income, College%, and Hispanic% display substantial coldspot overlap. Similarly, Poverty% and Rent% hotspots overlap significantly with many of the HET% cold spots in the northern Miami, Miami Springs, and Hialeah areas. The key takeaway from this LISA analysis is that there are visible overlaps in HET-VRP participation and the independent measures, validating the use of co-location join count tests to probe the bivariate spatial links between the dependent and independent measures in the following step of the county analysis.

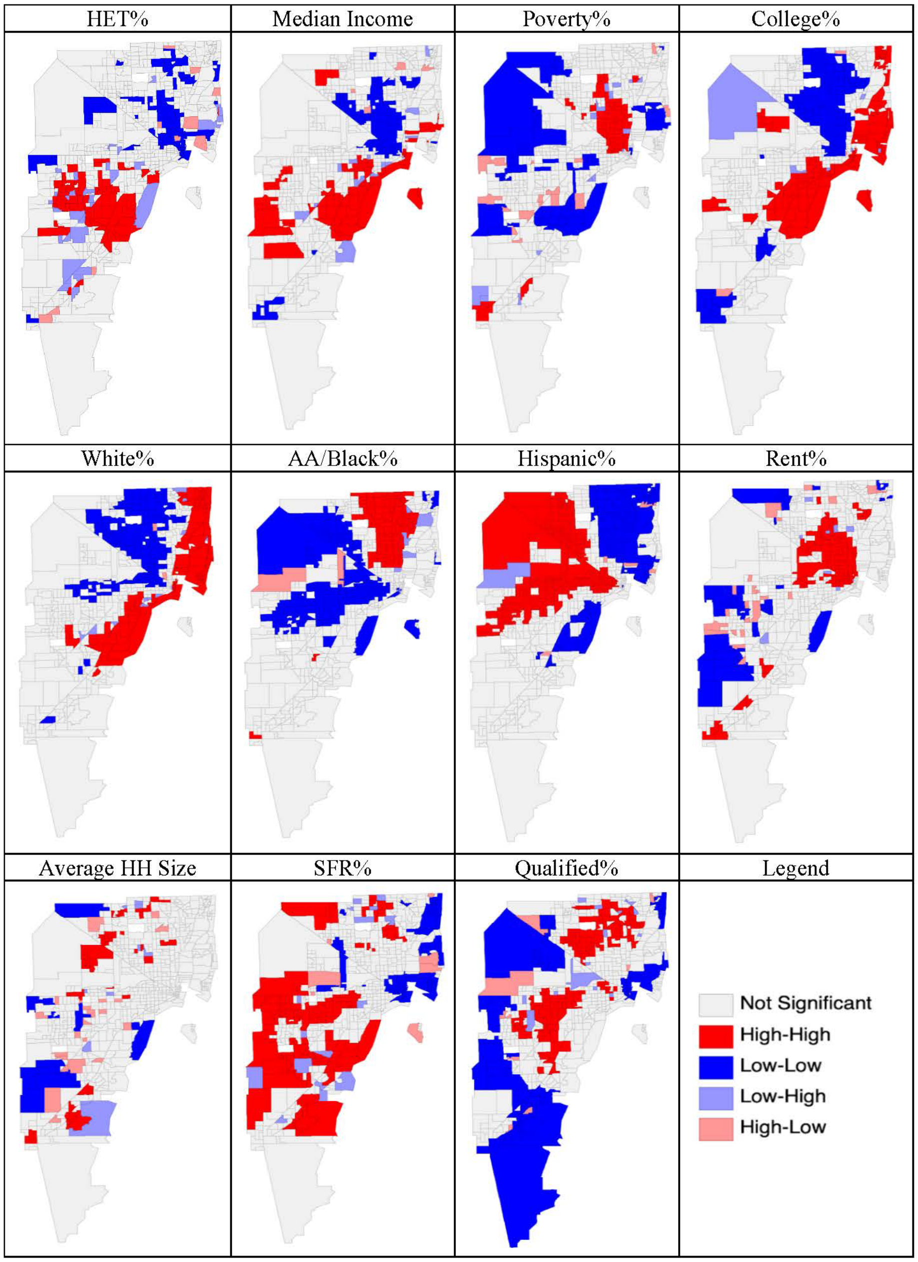

Fig. 6. Local Moran's I cluster results for county-level measures.

Fig. 7 provides the county-level binary co-location join count results (see Table A7 for the number of significant and insignificant county-level co-location join count census tracts). Overall, like the city-level results, the county results indicate a significant positive link between effectiveness measures and HET-VRP participation and a negative link between equity factors and HET-VRP participation. Notably, neighborhoods with the most qualified homes (built before 1996) also have the most HET-VRP participation, indicating participation is occurring the most in areas with the most qualified as expected from the effectiveness perspective. Additionally, the Fig. 7 proxy measure results indicate the county-level analysis aligns with the city-level observations, confirming that neighborhoods with higher income and educational levels, as well as greater percentages of white and Hispanic residents, are more likely to participate in the HET-VRP program validating the city-level analysis and results.

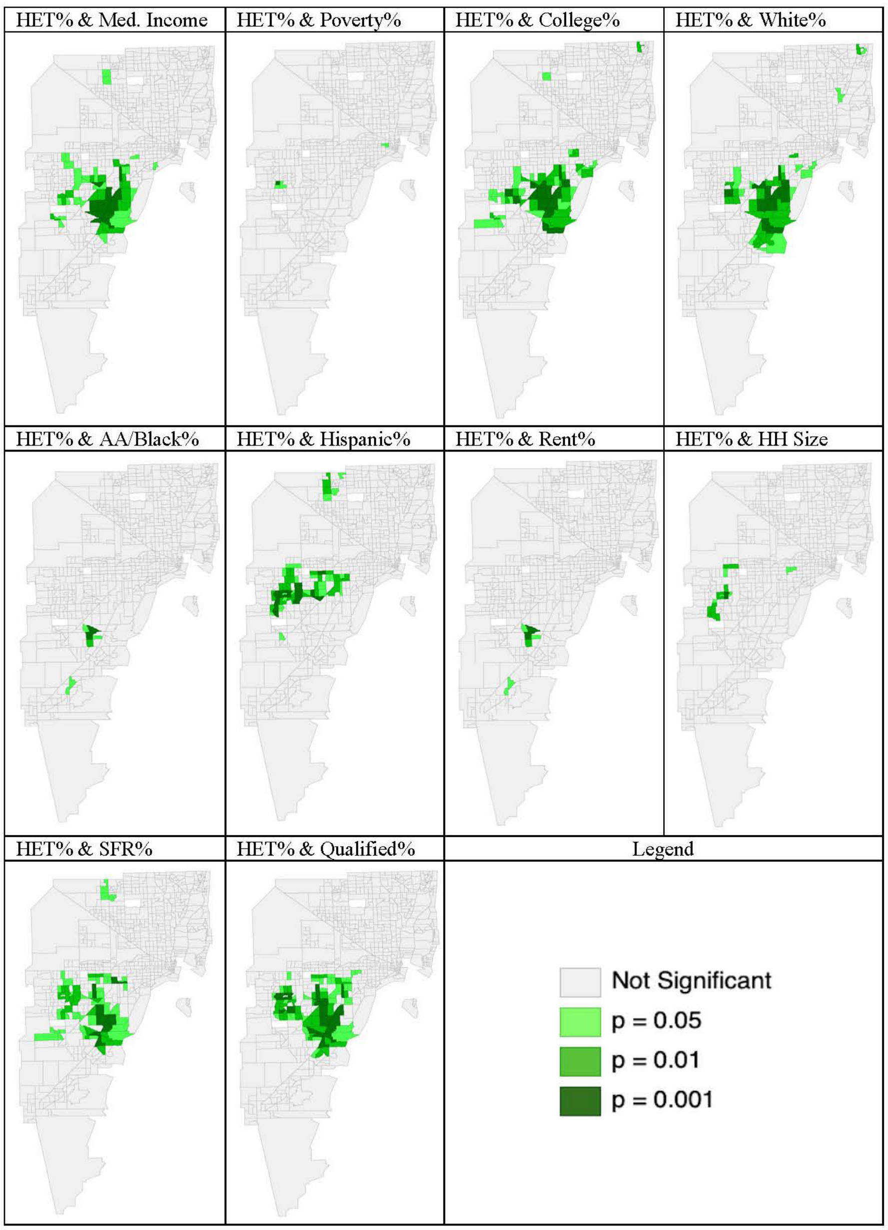

Fig. 7. Co-location join counts of county-level binary measures.

5. Discussion and conclusion

Local governments face multiple understudied tradeoffs related to the mix of policy instruments used in sustainable water management transitions (Clark et al., 2022; Farmer, 2022; Leigh and Lee, 2019). In this study, the research question and hypotheses focused on two critical facets: the effective reduction in residential water consumption and the equitable distribution of benefits derived from the program.

In terms of effectiveness, although Pearson correlation tests did not establish a significant statistical relationship between HET-VRP participation (HET%) and household water demand (GPHD) at the city level, likely due to the sensitivity to sample size, spatial analysis provides a different perspective. The co-location spatial tests demonstrate a significant link between HET% and GPHD, suggesting the program effectively targets areas with higher water consumption. This association is supported by findings from proxy measures in both city and county levels across parametric and spatial statistical tests. The observed neighborhood scale correlation between HET-VRP participation and higher water use further indicates the program's strategic focus and success in engaging households with high consumption, affirming the first hypothesis. These findings strongly suggest that neighborhoods with these characteristics are not only more likely to participate but also more likely to benefit from water-efficient technologies. As a result, the VRP successfully influences water conservation behavior among high-water consumption households (Lee et al., 2011), fulfilling one of its primary goals (Miami-Dade County, 2023). However, given that participation in any one neighborhood was less than 7% throughout the study period, WASD and other urban water utilities would likely benefit from increasing their current outreach efforts to increase program participation in the highest water use neighborhoods.

Regarding equity, our findings highlight a sobering counterpoint: economically burdened and ethnically diverse communities are notably underrepresented. This situation exposes a potential tension within the program's objectives—it appears to target high-consumption areas but might not be fulfilling other potential objectives, such as reaching communities that could most benefit from its financial incentives. The under-utilization in low-income, African American and Black households, rented households, larger-sized households, and those with a higher poverty percentage, evidenced by a lower HET VRP participation rate, affirms hypothesis two. Moreover, the fact that households with a disproportionate water cost burden relative to their income were less likely to engage with the program, which could help alleviate such burdens, underscores the need for equity planning in sustainability initiatives. These communities are the ones that could benefit most from the program's support (Conway et al., 2023; Matsler et al., 2023). Several factors might account for this participation gap: lack of program awareness, linguistic hurdles, or complications arising from landlord-tenant relationships in rented properties. Specifically, renters face unique challenges as they depend on landlords to make upgrades to high-efficiency infrastructure. Landlords, who often do not bear the water costs, may lack the incentive to invest in or navigate the complexities of VRP participation due to upfront costs and extensive paperwork.

Given the low percentage of HET participation in key areas of the city and county, as indicated by our spatial analysis, targeted outreach and addressing upfront costs of VRP participation could be two policy solutions to increase participation by these vulnerable groups. Outreach programs that target and align with the unique financial, cultural, linguistic, and traditional factors of these underrepresented communities may help bridge the existing participation gap. Additionally, it is likely important to consider the upfront costs associated with VRPs. Though VRPs provide a rebate after a household has participated, VRP's require initial expenditures, such as purchasing an appliance and covering installation charges. Initial costs could be a barrier to households with limited incomes; thus, offering upfront assistance to replace wasteful water appliances could enhance program participation, promote water conservation, and provide financial relief for households that face economic challenges. However, this approach could lead to increased costs for the utility, highlighting the inherent balancing act water managers must contend with. To balance effectiveness and equity, we recommend local decision-makers engage in comprehensive evaluation and public consultations to navigate these complex tradeoffs, ideally aiming for a policy that optimize both effectiveness and equity within the constraints of available resources.

The limitations of this study warrant that readers make conclusions from our results with caution, but they offer avenues for future scholarship. One of the primary challenges this study faced was data limitations. The research relied significantly on data from the Census Bureau's ACS and limited water use records. While these datasets offer invaluable information, they present certain constraints. For instance, using ACS 5-year estimates assumes that household characteristics remain unchanged throughout this period—a presumption that might not always be accurate. Moreover, our linear estimation procedure to predict the number of homes eligible for the HET rebate—based on the number of homes built prior to 2000—may overlook recent home renovations or upgrades, thereby altering their rebate eligibility. Additionally, our measure of high water consumption neighborhoods at the county-level, although innovative, relies on proxy variables at the county-level that might not fully capture the nuanced dynamics of water usage. Lastly, the scope of our dependent variable, HET%, is limited. It only accounts for households that utilized the rebate, excluding those that might have installed a HET without seeking a rebate. This could potentially underestimate the actual usage of HETs within the county and the city. Our study findings using publicly available and aggregated data provide interesting results, but future studies could overcome the aforementioned limitation by collecting granular household-level data. Granular data would help scholars and practitioners develop nuanced outreach methods that fit each community's unique and heterogeneous characteristics.

Despite data limitations, our study highlights the critical need for water conservation policies to balance effectiveness and equity. It underscores the importance of an integrated, socially inclusive approach to water management that protects resources and supports diverse communities. Our findings support the Curley et al. (2020) conceptual framework and emphasize the need to evaluate water conservation policies through a critical dual objective lens. Overall, this study provides both a conceptual and methodological approach for other scholars or practitioners to analyze the effectiveness and equity of local water conservation policy instruments.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

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