

What Conditions Support the Provision of High-Quality and Affordable Urban Drinking Water in the U.S.?

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ABSTRACT

Urban drinking water systems in the United States face diverse challenges and stressors, threatening their ability to reliably provide safe, affordable drinking water. To effectively address these challenges, utilities must understand the complex relationships among the community, biophysical, infrastructural, and institutional attributes of their system and how they impact overall system performance. In this study, we conduct a comparative case study analysis of 16 large-scale U.S. urban drinking water systems to identify underlying conditions associated with the provision of both affordable and high-quality drinking water. Using Qualitative Comparative Analysis and Non-Negative Matrix Factorization to analyze clusters of conditions related to diverse system attributes, we find that community attributes, including moderate

population growth and low poverty, play a significant role in shaping AQ outcomes. Moreover, there is an association between biophysical challenges and the development of robust institutional and infrastructural attributes. Cities confronted by marked biophysical challenges seem to be at the forefront in fostering adaptive institutional frameworks and proactive infrastructural measures. Concurrently, our study reveals that a water utility's commitment to conservation measures also impacts its performance in provision of affordable and high quality water. The study improves our understanding of the relationships between various attributes affecting the provision of affordable and high-quality urban drinking water. This can aid utilities in identifying pathways to ensure adequate service under increasing stress.

Keywords: Urban Drinking Water Systems. Comparative Case Study Analysis. Utility Performance. Water Affordability. Water Quality. QCA

INTRODUCTION

Urban drinking water systems in the United States (U.S.) face increasing stressors, such as changes in the quantity and quality of water supplies (AWWA 2023), deterioration of existing infrastructure (Pierce et al. 2019; Renwick et al. 2019; Nieuwenhuis et al. 2021; Silver 2021, AWWA 2023), and shifting urban demographics (Dieter 2018; Doyle et al. 2020; Pierce et al. 2021). These stressors challenge the ability of urban water suppliers to achieve their core mandate: providing reliable, safe and affordable drinking water to the communities they serve.

In recent years, both federal regulations and academic research have focused on drinking water quality challenges (Allaire et al. 2018; Bell et al. 2023), as communities across the country have experienced impaired water quality (e.g., the Flint lead crisis; Butler et al. 2016) and interruptions to the drinking water supply (e.g., the Elk River chemical spill in West Virginia; Bahadur and Samuels 2015). Additionally, the financial ramifications and institutional complexities involving regulated and unregulated contaminants pose a significant challenge, each carrying distinct economic implications and challenges for water utilities

(Laimer 2015). There is also growing recognition of equity concerns, with evidence showing that low-income and minority communities are particularly vulnerable to poor water access and quality (Roller et al. 2019; Mueller and Gasteyer 2021).

Another critical issue, however, is drinking water *affordability* (Mack and Wrase 2017; Luby et al. 2018; Meehan et al. 2020; Teodoro and Saywitz 2020; Goddard et al. 2022). For example, in the U.S. alone, EPA's 7th Drinking Water Infrastructure Needs Survey and Assessment (EPA 2023) estimates that the country will need to spend more than \$625 billion over the next 20-year period on water infrastructure, including pipes, treatment plants, and wastewater management facilities. Other studies estimate that climate change adaptations to water systems will cost the U.S. more than \$36 billion by 2050 (Jones and Moulton 2016). Although federal funding for water infrastructure improvements has increased in recent years, it still does not match the pace of needs and requirements (CWSRF 2023), leaving state and local governments to bear increasing financial burdens (Kane 2016; Hansen and Mullin 2022). Alongside these challenges, concerns about how to structure water rates to balance the competing objectives of maintaining revenue and promoting conservation during times of drought or scarcity are increasing (Massarutto 2020; Sowby and South 2023). In addition, declining population in some cities diminishes the customer base that must share the high fixed costs of water services. This is the case in Detroit, where a shrinking population means fewer residents who pay for water (Mack and Wrase 2017). Similarly, suburbanization, in cases where suburbs grow outside of the central city water system, leaves central city providers with fewer customers to pay for water services. This means that demographic dynamics combined with other pressures on urban water systems are likely to make water less affordable (Swain et al. 2020).

Disaggregating the diverse factors that shape urban drinking water systems' performance in relation to both water quality and affordability can help identify the root causes of problems and develop targeted solutions that provide adequate services (Freeman et al. 2018; Guo et al. 2018; Azizi and Meier 2021; Zhang et al. 2022). However, because the responsibilities for managing various challenges in urban water systems are delegated to various agencies or subagencies (Patterson and Doyle 2021; Bell et al. 2023), both data

collection and decision-making often focus only on specific aspects of a water system in isolation (Hughes and Mullin 2018; Hughes 2022). In recent years, there has been a call for more comprehensive data collection and analysis to better characterize water system features, evaluate performance, and improve the connection between water data and water management in the U.S. (Josset et al. 2019; Sugg 2022; Bell et al. 2023).

Few studies have investigated the relationships between different attributes of water systems and how they collectively impact system performance. One study that begins to address this nexus is Bell et al. (2023), which explores of the interconnected dimensions of North Carolina's water systems, including biophysical, demographic, financial, and technical aspects. The researchers make a compelling case that the financial vulnerabilities of a water system are closely tied to the income base of its service area. This link poses a significant challenge as many systems struggle to balance the need for sufficient revenue generation with maintaining affordability for consumers. Additionally, the study found that indicators incorporating revenue generation provide more informative measures of fiscal vulnerability than the overall debt burden. While regionally-focused, Bell et al.'s (2023) study contributes valuable insights to an evolving research field with potentially wider implications. A careful review of the system indicators they used reveals opportunities for further exploration. Such an expansion could help elucidate a more nuanced understanding of the pivotal factors impacting a utility's ability to provide high-quality and affordable drinking water.

This study is thus motivated by the need for a more comprehensive understanding of how the diverse aspects of urban water systems affect performance outcomes, both alone and interdependently. To advance knowledge in this area, we relate water quality and affordability outcomes of 16 large U.S. water systems to specific system attributes, seeking to identify key determinants and their interdependencies. The results of the study reveal that achieving high-quality and affordable urban drinking water systems can be attained through various approaches, each influenced by specific conditions. Key factors affecting the

performance of these systems encompass moderate population growth, reduced poverty levels, increased adoption of conservation strategies, and maintained infrastructure condition.

MATERIAL and METHODS

To better understand the performance of urban water systems, we first identify and classify various factors expected to affect water system performance into community, biophysical, institutional, and infrastructural system attributes, all of which have been shown to impact the quality and affordability of water services (Javernick-Will et al. 2018; Jama and Mourad 2019; Dobbin et al. 2021). We then employ the complementary methods of Qualitative Comparative Analysis (QCA) and non-negative matrix factorization (NNMF) to analyze the impact of these factors on utility performance. QCA was chosen to assess potential necessary and sufficient conditions associated with an outcome of interest, and it is suitable for relatively small sample sets (Knieper and Pahl-Wostl 2016). NNMF complements QCA by identifying patterns and relationships in the data from a different perspective, without the consideration of outcomes. NNMF can provide a check on QCA findings and offer additional insights into the relationships between conditions and utility performance. NNMF is also well-suited for datasets with numerous independent variables and no negative variables (Paatero and Tapper 1994).

Case studies

We selected 16 large U.S. cities that represent diverse water management structures, geographic locations, water supply portfolios and community characteristics that may affect their response to various stressors and their performance. These case study cities were chosen based on the study by Deslatte et al. (2022), in which 16 cases were selected from a pool of 197 large cities based on attributes of the community, biophysical properties, institutional characteristics, and indicators of transition towards sustainability. Factors such as the partisan voting index, population growth rate, per capita personal income, the Köppen aridity index, percent surface water, the state-level water rights regime (e.g., prior appropriation vs. riparian water rights), and the Vanderbilt Water Conservation Index (Hess et al. 2017) were considered for case

selection (Fig. 1 and Table 1). By comparing these cases, we aim to assess the co-occurrence of conditions associated with key system attributes and how they relate to system performance regarding the provision of high-quality and affordable water.

The key challenges facing the 16 selected urban water systems, defined by their main utility boundaries, were identified from utility reports, academic studies, and news articles. The challenges often vary regionally. For instance, cities in the Eastern U.S. may most commonly grapple with negative population growth rates and aging infrastructure, while cities in the Western U.S. encounter challenges related to climate change and water availability (Table 1).

Data description

We assembled data associated with the community, biophysical, infrastructural, and institutional attributes of each system (Table 2). We identified the attributes and their corresponding conditions based on our fundamental understanding of the structure of urban water systems and the current challenges they face. Our approach was guided by a review of the existing literature, focusing on discerning the critical aspects of these types of systems (Deslatte et al. 2022). We also assembled data to develop two indicators of system performance: a water quality index and an affordability score (Raw data is summarized in Table S1 and S2). The attributes, their underlying conditions, and performance indicators will be described in more detail next.

Biophysical attributes

The biophysical attributes of the water supply and associated infrastructure have a significant impact on the quality and reliability of drinking water. For example, the quantity of water available for municipal supply depends in part on hydroclimatic conditions such as precipitation and temperature, and geomorphologic conditions such as the size and slope of the watershed, the soil texture, vegetation types, and land use (Price et al. 2011; Libisch- Lehner et al. 2019). However, a system's available water supply is not solely determined by these physical and climatic factors; it is also shaped by the infrastructure's capacity to distribute water and the dynamics of demand. Thus, we selected two variables (Table 2) that are

hypothesized to impact urban water supply performance: the adequacy of the water supply, which is measured by the ratio of water demand to supply (McNulty et al. 2007; Treuer et al. 2017), and the water demand per person (Treuer et al. 2017). Note that water supply is computed as the minimum of hydrologically, legal and infrastructurally available water. To compute these variables, we collected data from publicly available utility reports on surface and groundwater rights, pumping and withdrawal permits, water stored in reservoirs and groundwater banks, water use, population, and the capacity of reservoir, aquifer recharge systems, transmission pipelines or canals, and treatment plants. While we expect these conditions to vary in time, we use measures from a single point in time to analyze a snapshot of utility performance.

Infrastructural attributes

Many water systems are facing challenges related to aging and deteriorating infrastructure, which affects individual households and communities (AWWA 2020). Four variables representing the conditions of hard infrastructures within systems and their functionality were chosen including water main breaks, non-revenue water, system density and depreciation rate. First, water main breaks (Folkman 2018) and non-revenue water (AWWA 2016) (defined as the volumetric difference between water supply input and the volume of billed water resulting from leaks, metering inaccuracies, and unauthorized consumption) data were gathered from various sources, such as financial reports and capital improvement plans, among others. This data was then combined into a single metric using multiplication (calibrated Non-revenue condition in QCA process multiplied by calibrated Breaks results infrastructure conditions, Table S3). Since the two conditions (i.e., water main breaks and non-revenue water) are highly correlated, one measure can compensate for the other when data is missing (in the calibration process, if data for a case was not available, we considered the corresponding value to be 1). Next, system density, defined as the total length of water distribution pipes per population served, is included to indicate challenges that arise with geographically dispersed systems. Finally, depreciation per mile can be used to account for the system's aging infrastructure (Cabrera et al. 2013). Depreciation is defined as the decrease in the value of water

infrastructure systems (based on materials and environmental exposure) that occurs over the course of their life, which ranges from 75 to 100 years for all cases in this study (ASCE 2021). Depreciation data were gathered from comprehensive annual financial reports (CAFRs) for each utility.

Community attributes

Several attributes of the community influence the functioning of water systems, including the system's ability to finance operations, infrastructure development, and maintenance (Marques et al. 2015; Hansen and Mullin 2022). We chose population growth, the Gini index (an index of income inequality), and the fraction of the population below the poverty level to represent community attributes, as they provide insight into the community's economic and demographic characteristics and their potential impact on the financial stability and sustainability of the water system (Rogers et al. 2020).

Institutional attributes

In the context of water system management, institutional attributes refer to the organizational structures, policies, and strategies that enable effective operation, maintenance, and planning. These include managing infrastructure functionality, financing operating expenses, strategic planning, and policy-making (Leigh et al. 2019). In this study, we primarily focus on financial conditions, given their pivotal role in ensuring the sustainability of water systems (Herman et al. 2015; Garcia et al. 2019). The financial conditions we examined include the operating ratio (calculated as revenues divided by expenditure), debt-service coverage ratio, and total liabilities to total assets ratio. All were derived from financial data extracted from publicly available annual utility financial reports (e.g., City of Providence 2021). Most water systems fund capital projects from rate collection and borrowing (bonds). To support these investments, sufficient revenue is required to repay the principal and interest (Rodriguez et al. 2012). To capture that aspect of the system, we also collected total investment per capita from Capital Improvement Program reports that each utility made for their water supply, water distribution systems, and other capital expenses. In addition to these financial conditions, we included the Vanderbilt Water Conservation Index (VWCI) as a measure of

sustainable water management because it demonstrates the extent to which cities have adopted water conservation and demand management practices (Hess et al. 2017).

Performance attributes

Water utilities strive to provide high-quality water to consumers at an affordable price. To measure system performance in these areas, we developed metrics for water quality and affordability. Our water quality index is based on the maximum concentration of all measured samples for total trihalomethanes and haloacetic acids-5 as reported by utilities in their annual water quality reports to the US Environmental Protection Agency (USEPA) in 2021. While this index places emphasis on these two contaminants, it is worth noting that these were not the only factors considered. As referenced in Table S2, our evaluation encompassed a wider range of contaminants, including barium, chlorine, fluoride, nitrate, total coliform bacteria, and lead. However, total trihalomethanes and haloacetic acids-5 were specifically spotlighted because they were the sole contaminants found to exceed the maximum concentration level (for single measure) set by the USEPA in some of our case studies, as none of the utilities were in violation or non-compliance with EPA standards throughout 2021. The Household Burden Indicator (HBI) was used as a performance condition for affordability. HBI evaluates the cost of basic water services as a percentage of a household's 20th percentile income (i.e., the Lowest Quintile of Income (LQI) in the Service Area). To determine the cost, the monthly volumetric rates for water and sewer services are multiplied by 50 gallons (189.3 Liters) per person per household per day, a reasonable estimate of basic water usage (Teodoro 2018; Raucher et al. 2019; Patterson and Doyle 2021; Cardoso and Wichman 2022; Hayman et al. 2022). Raucher et al. (2019) considers households with combined water costs below 7% of their LQI as low-burden, while Teodoro (2018) suggests a threshold of 10% of disposable income. In this analysis, we adopt the affordability benchmark of 7% of total gross income spent on water services. We also assume an average household size of four, which corresponds to 800 cubic feet of water (3.03 m³) consumption per month. This assumption is larger than the average US household size of 2.64, as reported by the ACS (2021),

providing a more conservative measure of affordability according to Teodoro (2018). However, this conservative impact is counterbalanced by the use of total gross income in the calculations.

Qualitative comparative analysis

Qualitative Comparative Analysis (QCA), developed by Ragin (1987; 2006; 2008), is a method used to examine specific outcome measures and their associated conditions across cases. Utilizing Boolean algebra, this approach simplifies the complexity of causation, enabling comparisons across different cases and uncovering common patterns and relationships between conditions and outcomes. QCA typically involves four core steps discussed below (described further in the supplementary materials). Additionally, we conducted a sensitivity analysis to assess the robustness and reliability of our results.

1. Conceptualization of cases and conditions: We analyzed 16 cases based on thirteen conditions underlying four attributes. Despite the potential for uniqueness issues (Marx, 2006), further analysis showed maintaining all 13 variables was viable and necessary for a thorough exploration (Table S8 and Fig. S1).

2. Operationalization and calibration: We defined the outcome measure as the product of an affordability indicator and a water quality indicator. The affordability indicator is set to 1 for cities where the water bill is less than 7% of the income of the lowest 20% of the population and set to zero for cities with higher water bills. The water quality indicator is set to zero if a city reported any single measured concentration above 110% of the maximum concentration level (MCL) set by the EPA and is set to 1 otherwise. When both affordability and water quality thresholds are met, the product of indicators is 1 and the outcome is referred to as a “high-AQ score” (where A represents affordability and Q represents quality). Conversely, when either the affordability or water quality indicator is zero, the product is likewise zero, and the outcome is referred to as a “low-AQ score”. The calibration of conditions (further details in the supplementary materials), both crisp and fuzzy, has been detailed as per standard QCA literature (Berg-Schlosser et al. 2009; Ragin 2008).

248 3. *Construction of a truth table*: The truth table cataloged possible combinations of conditions and
249 their outcomes (Schneider and Wagemann, 2012). This placement considers the number of cases
250 conforming to each specific combination and their consistency scores, which range from 0 to 1 and refer to
251 the proportion of similar causal configurations leading to the same outcome value. For instance, a
252 consistency score of 0.8 indicates that 80% of cases with a particular combination of conditions resulted in
253 the same outcome. We also utilized coverage as a metric in our QCA, which measures the degree of overlap
254 between two sets relative to the larger set, with values ranging from 0 to 1. We maintained a minimum
255 number of cases per condition combination at one due to our sample size and set our consistency threshold
256 at 0.75 as per recommendations (Rihoux and Ragin, 2009; Schneider and Wagemann, 2012). Due to our
257 study's exploratory nature, we didn't establish a fixed coverage threshold, aiming for broader data
258 exploration even at the risk of increased interpretative complexity. While higher coverage is generally
259 better, there is no commonly agreed minimum coverage a QCA analysis must reach for the results to be
260 considered valid (Fainshmidt et al. 2020).

261 4. *Necessity and sufficiency analysis*: this pivotal step in QCA involves assessing the roles of
262 conditions in generating specific outcomes. The necessity analysis evaluates whether a condition is
263 indispensable for an outcome's occurrence. Here, a condition is labeled as necessary if its existence is
264 crucial for the outcome to occur. On the other hand, a condition is deemed sufficient if its presence
265 invariably prompts the desired outcome (Marx et al. 2014). However, it is important to note that in complex
266 systems, outcomes often depend on a combination of conditions rather than a single factor. Therefore,
267 sufficiency analysis shifts the focus to identifying "configurations of conditions" – specific combinations
268 of conditions that, when present together, are sufficient to result in the outcome. With the aid of the truth
269 table, QCA facilitates the identification of these sufficient configurations of conditions.

270 5. *Sensitivity analysis on QCA*: The calibration of fuzzy sets in QCA must be grounded in
271 theoretical and empirical knowledge of a topic (Ragin 2008). Therefore, to ensure the validity of our
272 findings and reduce subjectivity in the output, we integrated a reliability analysis on the crossover point

threshold into our QCA analysis. This reliability analysis provides a range of confidence for the results commonly presented in QCA, such as consistency and coverage. To achieve this, we conducted three QCA analyses based on different thresholds:

- QCA (M), assuming that the crossover point is equal to the data sets average (Table S3).
- QCA (M⁺), increasing the probability of obtaining a higher membership score for any condition by moving the crossover point closer to the non-membership score by 25% of the interval between the crossover point and non-membership score in the QCA(M).
- QCA (M⁻), decreasing the probability of obtaining a higher membership score for any condition by moving the crossover point closer to the membership score by 25% of the interval between the crossover point and membership score in the QCA(M).

We then compared the range of variability across different conditions corresponding to outcome for these three scenarios. The QCA analyses performed on M⁺ and M⁻ represent the boundaries of the analysis and the validity of the different solution sets (Table S7 for more information).

Our QCA followed the method applied by Baggio et al. (2016) for the co-occurrence of drivers in explaining success and failure in the commons. The in-depth details pertaining to the calibration process, as well as other technical aspects of the QCA methodology, including discussions about the rationale for the set thresholds, are provided in the supplementary material. The material also includes a comprehensive presentation of the truth table, displaying the combination of conditions linked to the outcome of interest.

Non-negative matrix factorization

As the calibrated matrix from conditions and cases was constructed in the previous stage, we applied dimensional reduction to assess the relationship between conditions in different cases and compare the findings with QCA. Because the calibrated matrix has no negative values, it is a good candidate for non-negative matrix factorization (NNMF). NNMF is a multivariate statistical analysis method, usually used to decompose the sample data matrix into two matrices (Paatero and Tapper 1994), factor contributions and

factor profiles from non-negative datasets (Eq. 1). This approach can provide insight into the underlying patterns and relationships in the data, and thus serves as a complementary approach to help validate the findings from QCA and provide additional insights into the relationships between conditions and cases. The primary equation for NNMF is:

$$X_{nm} \approx \sum_{j=1}^p G_{np} \times F_{pm} \quad (1)$$

where X_{nm} is the original matrix ($n \times m$), representing n cases and m monitoring conditions, which can be decomposed into two matrices G_{np} ($n \times p$) and F_{pm} ($p \times m$), where p represents the number of calculated sources (components or extraction factor); G is the source contribution matrix; F is the source spectral matrix (factor load). Details on the NNMF algorithm and its implementation are discussed by Paatero and Tapper (1994).

In this study, we applied NNMF using two components ($p = 2$). By applying NNMF, data for the cities can be represented in the two-dimensional space ($G_{16 \times 2}$) as well as conditions ($F_{2 \times 13}$) along with the vectors that indicate the component weights for both matrices.

RESULTS

In our analysis of 16 cases, 10 were identified as high-AQ cases and 6 as low-AQ cases. The results of this analysis, presented in Figs. 2-5, reveal that certain combinations of conditions are associated with high-AQ scores. In the following sections, we provide a detailed breakdown of these findings from both the QCA and NNMF analyses.

Attribute configurations associated with outcomes

The necessity analysis in our study seeks to determine whether a condition is crucial for achieving a high-AQ outcome. The results (Table 3) show that the condition “Pop” (population) scores among the highest, indicating its significant role. Similarly, “Sup” (water supply adequacy) and “Lia” (liability asset ratio) also

demonstrate substantial necessity scores. However, with no condition reaching a consistency score of 1, no single factor is strictly necessary to attain a high-AQ score.

The sufficiency analysis, which forms the second component of the QCA, is designed to identify combinations of conditions that are sufficient to achieve a high-AQ outcome. These combinations, often referred to as “pathways”, are, in themselves, enough to result in the desired outcome. From the analysis (Table 3), several combinations were identified as being sufficient for a high-AQ outcome. Each combination represents a unique blend of conditions that, when present together, lead to the high-AQ outcome. For example, the first combination in Table 3 has a perfect consistency score (1), implying that whenever this set of conditions was observed, a high-AQ outcome ensued. This combination accounts for 8% of all high-AQ outcomes, as denoted by its coverage score of 0.08. It should be noted, however, that the focus of this analysis was not merely to find unique configurations but rather to identify potential commonalities among the conditions contributing to high-AQ outcomes.

Results show that each combination of conditions creates a unique pathway to achieve an outcomes. For instance, the first combination in high-AQ outcomes might be representative of areas with moderate population growth, lesser poverty, and a low degree infrastructure depreciation, among other factors, that collectively yield a high-AQ outcome. These combinations emphasize that a mix of conditions, not a singular factor, contributes to achieving high-AQ outcomes, underscoring the complexity of the studied phenomenon.

Additionally, certain conditions emerge more frequently in these combinations, which indicates the relative importance of a condition’s association with the specified outcome across cases (Fig. 2; more details in supplementary material, Section 2). The result suggests that higher levels of investment are prominent in cases of low-AQ score and moderate population growth, lower poverty, and better infrastructure condition are prominent in high-AQ score cases. Conversely, conditions such as lower water supply stress and higher operating ratio occurred relatively frequently in both outcomes. Furthermore, conditions such as lower depreciation and lower system density occurred rarely in both outcomes.

The QCA reveals that the co-occurrence of certain conditions can increase the likelihood of obtaining a high-AQ score, with normalized frequency analyses uncovering distinctive patterns of mutual association between these conditions and AQ scores (Fig. 3). Conditions co-occur in both outcome cases; however, co-occurrence is more prominent in high-AQ score cases (i.e., there are a greater number of values above 0.5 in the co-occurrence matrix for high-AQ scores). This suggests that there are certain groups of conditions that are present jointly in high-AQ scores, but not in low-AQ cases.

In high-AQ score cases, we found a high likelihood of co-occurrence of the conditions low water supply stress, low poverty, and moderate population growth (Fig. 3). Additionally, our findings suggest that when these conditions co-occur, there is an increased likelihood of co-occurrence with both better infrastructure condition and higher liability asset ratio. Moreover, there is a relatively high probability of co-occurrence between better infrastructure condition and higher liability asset ratio in high-AQ cases. Interestingly, the co-occurrence between these conditions was found to be low in cases with low-AQ scores, suggesting that the joint occurrence of these conditions may be particularly important in contributing to high-AQ outcomes. On the other hand, conditions such as the total investment in water system, distribution system density, and depreciation of system are found to be less frequent in cases with high-AQ score compared to other co-occurring conditions.

While the co-occurrence of conditions is less prominent in low-AQ score cases, some conditions are more likely to co-occur than others. For example, we found that low water supply stress and low water demand per person have a higher probability of co-occurrence. Additionally, a low Gini index and low investment in water system were also found to have a higher likelihood of co-occurrence. The lower co-occurrence of these conditions in cases with high-AQ scores suggests that their joint occurrence may be associated with low-AQ outcomes. It is important to note that the analysis conducted so far does not distinguish between different patterns of condition configuration paths and their relationship to AQ outcomes. In the next step, we will consider the frequency of conditions in association with AQ scores.

The results thus far suggest that low poverty, moderate population growth, and better infrastructure conditions (low non-revenue water and water main breaks) are strongly associated with the assignment of the higher AQ score. However, it is important to interpret the results derived from QCA with caution due to the sensitivity of the approach to the established thresholds. A sensitivity analysis of thresholds (Fig. 4) indicates that differences in frequency of occurrence in infrastructure, investments, population growth, poverty, and supply between high-AQ and low-AQ cases are robust as their variability ranges do not overlap. On the other hand, the inferred differences between AQ cases for liability asset ratio and conservation are fragile given the broad overlap determined by the sensitivity analysis.

Examining the QCA results from a broader viewpoint and accounting for the combined occurrence of various conditions across all cases suggest a positive association between the total number of present conditions in a case study (i.e., conditions meeting a certain membership score) and the likelihood of a system being assigned a high-AQ score (Fig. S1 and Table 4). On average, the high-AQ score cases had 7.8 ± 1.6 (max=10) present conditions, while the low-AQ score cases had an average of 6.1 ± 1.2 .

When we break down the conditions by attributes (defined in sections above), the distribution of conditions presents another interesting pattern (Table 4). In cases with low AQ scores, the prevalence of conditions related to biophysical attributes was notable, with an average of 75% of conditions within this category being present. In contrast, high-AQ score cases significantly outpaced low-AQ score cases in the number of present conditions related to community and institutional attributes (73% and 50% respectively, compared to 33% and 35% for low-AQ score cases), and also demonstrated a higher prevalence of infrastructure attributes (Table 4).

Dimensionality reduction and comparison with QCA

The NMF results show differences in the weights assigned to different cities and conditions, as represented by the two components in Fig. 6. These results can be interpreted in conjunction with the findings obtained using QCA analysis. For instance, Toledo, Harrisburg, Detroit, and Hartford group together in component 1 as all have a high correlation with this component (based on slope), while Boston,

Jacksonville, Sacramento, Santa Rosa, and San Jose form a separate group in another component (component 2). Additionally, population growth, conservation, infrastructure, and poverty are found to have a strong correlation with the first component (based on slope), while operating ratio, investment in water system, and water demand have a strong correlation with the second component.

The NNMF results are broadly consistent with the themes derived from the QCA. For example, the conditions that have a strong correlation with component 1 in Fig. 6 (Pop, Cons, Inf, and Pov) are also commonly associated with high-AQ score cases, including Boston, Santa Rosa, Sacramento, and San Jose. On the other hand, the conditions that have a strong correlation with component 2 are typically linked to low-AQ score cases, including Toledo, Harrisburg, Memphis, Hartford, and Atlanta.

DISCUSSION

Our findings indicate that generally, low AQ scores tend to be strongly associated with biophysical attributes e.g. a low aridity index is associated with a low AQ score. Interestingly, this suggests that more favorable environmental conditions, such as abundant water resources, might paradoxically hinder the system's capacity to adapt. On the other hand, cases associated with high-AQ scores tended to be strongly associated with institutional and infrastructure attributes, although the latter were relatively less prominent. Interestingly, these high-AQ systems appear to be more burdened by challenging biophysical conditions. This adversity could potentially stimulate the redirection of resources and energy toward the development of institutional and infrastructure attributes. Hence, this might suggest a positive interplay between the presence of harsh biophysical conditions and the emergence of robust institutional and infrastructure attributes. For context, cities such as Harrisburg, Hartford, and Detroit, despite having better biophysical attributes, register lower scores in both the institutional conditions such as conservation index and infrastructure conditions. Meanwhile, cities facing more challenging biophysical conditions like Phoenix, Santa Rosa, San Jose, Providence, and San Jose, demonstrate higher metrics in conservation and infrastructure. This contrast might root back to historically more adaptable institutional structures in the latter group. The evolving nature of policy responses, especially when confronted with potential challenges,

underscores a forward-thinking stance, highlighting a shift in resource allocation and strategic planning. Moreover, the marked presence of community attributes in high-AQ score cases highlights the crucial part that communities play in bolstering and enhancing system performance. The association between community attributes and high AQ scores might reflect the community's capacity to mobilize and adapt in the face of changing conditions, thereby boosting the overall AQ score of the system.

More detailed analysis revealed that a combination of conditions, including low poverty, moderate population growth, and better infrastructure conditions, play an important role in achieving high-AQ scores in urban drinking water systems. This underscores the importance of considering multiple attributes when designing and implementing water management strategies, as well as continuously monitoring and adjusting these strategies to address evolving challenges (Brown and Farrelly 2009).

High-AQ score cities

Western cities, such as Sacramento, Santa Rosa, and San Jose, exhibit similar patterns of positive population growth, financial stability, favorable infrastructure conditions, and appropriate levels of system investment. A high conservation score, represented by a greater number of measures that a city has taken to reduce its water demand (Hess et al. 2017), was identified as a shared condition among these cities. This score is based on a list of 79 possible policy actions, such as watering limitations, rebates, billing structures, and more. This reflects the cities' adoption of conservation and demand management practices (Gilligan et al. 2018). This also suggests that cities with similar geographic and climatic conditions can benefit from examining successful examples and adopting similar strategies to improve their water systems (Dieperink et al. 2023).

Boston, another high-AQ scoring city, shares similarities with the aforementioned western cities despite significant differences in geographical and climatic features. Factors such as positive population growth, balanced financial stability, and suitable levels of system investment are associated with its high-AQ score. Although aging infrastructure poses challenges for many eastern U.S. cities, Boston's high

system density likely contributes to success in addressing infrastructure issues, such as water main breaks, non-revenue water, infrastructure depreciation, and water quality problems.

Providence, Phoenix, Charlotte, and Indianapolis achieved high-AQ scores while facing different challenges. Providence maintained a high-AQ score through effective water management strategies, addressing issues arising from its system size and maintaining a manageable operational ratio and low levels of depreciation. Phoenix and Charlotte implemented effective water conservation measures and capitalized on their rapidly growing population to invest in infrastructure improvements. Indianapolis has favorable community attributes and proactive infrastructure management, demonstrating the importance of targeted investments and proactive management in achieving favorable water system outcomes. In the case of Memphis and Washington DC, both cities achieved high-AQ scores despite some unfavorable conditions such as infrastructure and conservation programs (in both cases) and community attributes (in the case of Memphis). Their success may be attributed to effectively managing financial conditions as seen in their operational ratio and debt service coverage.

Low-AQ score cities

Among low-AQ cases, four cities (Harrisburg, Hartford, Jacksonville, and Toledo) had relatively low water quality scores, while four others (Atlanta, Detroit, Hartford, and Toledo) were relatively less affordable. Jacksonville shares most of the conditions identified associated with high-AQ cases, specifically Sacramento, Santa Rosa, San Jose, and Boston. Lower scores on infrastructure conditions (high non-revenue water and frequent water main breaks) may explain the different outcome value observed in Jacksonville. The relatively lower water quality scores of Harrisburg and Toledo are the reason that these cities fall into our low-AQ class. Note that our water quality score is based simply on the maximum measured concentration reported by the utility for just two contaminants, both of which are disinfection by-products. The water quality is overall high as none of the utilities were in violation of EPA standards. Excursions from the norm reflected in the maximum observed concentrations in routine measurements were presumably handled expeditiously by the utilities to correct treatment conditions and reduce the

concentrations of the contaminants. This underscores the need for a nuanced understanding of the specific challenges faced by each city and the development of tailored strategies to address them (Pahl-Wostl et al. 2013).

In terms of water affordability, Midwestern cities, such as Toledo and Detroit, face similar challenges related to population growth, poverty, and infrastructure. For example, Detroit has struggled with individual water shutoffs due to lack of payments from customers, resulting in financial problems and further infrastructure challenges (Heil 2022). Despite these issues, these cities have invested in their water systems by seeking external funding sources, leading to higher investment scores compared to other similar cases. This demonstrates the potential for cities to improve their water systems by exploring alternative funding mechanisms and leveraging available resources to overcome financial and infrastructural challenges (Bell et al. 2023).

Hartford faces unique challenges, including negative population growth, aging infrastructure, and a significantly larger system size compared to cities with similar geographical and climatic features (e.g., Boston and Providence). These conditions may increase the likelihood of water quality issues and drive-up water prices to address challenges, making water supply in Hartford less affordable, ultimately leading to a low-AQ score outcome. This highlights the importance of addressing the root causes of such challenges, such as population decline and aging infrastructure, to improve water system performance.

Challenges and future data considerations

The limitations of this study include the fact that it only examines snapshots of urban water system conditions and does not account for changes over time. As described by Rothman and Greenland (2005), understanding the causal conditions more clearly requires careful consideration of the antecedent conditions, the conditions that led to the outcomes, and the strategies employed to address them. Additionally, the institutional context of our analysis may not be generalizable, as each utility may have unique approaches and conditions that potentially contribute to high-quality and affordable water service.

Building on recent insights into utility financial strategies, our analysis acknowledges the intricacies of debt covenants utilities must navigate (Gorelick et al. 2023). Utilities are often bound by such covenants, even if not always directly tied to the debt service coverage ratio. As these ratios serve as pivotal indicators for assessing financial health, it is worth noting that a lower debt service coverage ratio does not inherently denote financial distress. In fact, utilities strategically maintain ratios slightly above predetermined levels to manage optimal debt, fulfilling both covenant requirements and budgetary considerations (AWWA 2011). The uniqueness of each utility's institutional context, as highlighted in our analysis, therefore underscores the nuanced approach to water service delivery, emphasizing the balance between quality and affordability. Furthermore, the limited number of cases and the calibration procedure may introduce bias in the analysis. Additionally, the AQ score criteria applied, the lack of possible important contextual variables, and the simplification of some variables (some of which may need more in-depth analysis because they are composites of multiple conditions) may also influence the results.

To improve the robustness of our findings, more comprehensive and in-depth data could be assembled by studying a larger number of cases over an extended period of time. This would increase the statistical power of our results and provide a more nuanced understanding of the relationship between various conditions and outcomes. A larger sample size would also help to reduce the influence of any outliers or confounding conditions and increase the generalizability of the results. Additionally, further research should be conducted to identify other important contextual conditions that may be influencing the results. For example, it would be valuable to investigate the financial strategies water providers adopt in varying economic climates, particularly in relation to the issuance of refunding bonds at more favorable interest rates and the implications of annual budget rate changes. This could provide insights into how these entities navigate financial systems to alleviate pressures on ratepayers while ensuring sustainable infrastructure investments. Moreover, another variable that could enrich future analyses is the consideration of utility employee retention, especially in light of the looming “grey wave” of retirements (Dickerson and

Butler 2018). The ratio of utility full-time employees to the community size, along with the trend of unfilled positions, may offer insights into institutional resilience and capacity challenges faced by utilities.

CONCLUSION

Our results highlight that achieving a desired outcome can be pursued through multiple pathways, which are linked to the presence or absence of certain conditions. But, for a better understanding of how these conditions affect the outcome, it is necessary to consider them collectively rather than in isolation. We found that community attributes play an important role in shaping AQ outcomes. Given their significant impact, especially in areas with high/low population growth and high poverty, utilities should prioritize strategies that empower communities and implement policies targeting vulnerable populations to enhance water affordability and ensure equitable access to clean water resources. Moreover, rather than focusing solely on biophysical conditions, there's a pressing need to account for institutional dynamics, as our findings suggest their integral role in shaping AQ scores. Infrastructure condition remains a cornerstone for system performance; thus, ensuring its proper state through regular audits, maintenance, and timely upgrades is of crucial importance. Furthermore, based on our study findings, adopting conservation strategies could also potentially contribute to higher AQ scores.

Data Availability Statement

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

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Supplemental Materials

The Supplemental Materials for this manuscript consist of four specific subsections: qualitative comparative analysis, QCA implementation, QCA results, and QCA results using six variables. Details of these subsections can be found in the figures and tables provided. Specifically, Figure S1–S2 and Tables S1–S8 can be accessed online at the ASCE Library (www.ascelibrary.org).

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Table 1. General characteristics of case studies.

City Name	Abbr.	Utility	Utility Type (muni/private)	Water Supply source		Main water challenges
				Surface water %	Ground water %	
Atlanta, GA	ATL	Department of Watershed Management	municipal water utility	100	0	Water stress and scarcity due to climate change and, consequently, decrease in river streamflow Low resilience to droughts High water price that affects low-income residents Flooding and water quality challenges of stormwater collection Expected longer heat waves and higher number of hot days due to climate change, causing rates of evaporation in rivers and lakes to increase
Boston, MA	BOS	Boston Water and Sewer Commission	municipal water utility	100	0	Aging infrastructure Flooding and water quality challenges of stormwater collection Complex water management system Expected higher number of hot days and sea level rise due to climate change
Charlotte, NC	CHA	Charlotte Water	municipal water utility	100	0	Water stress due to the increase in population and demand Aging infrastructure Expected higher number of hot days and stronger hurricanes
Detroit, MI	DET	Detroit Water and Sewerage Department	municipal water utility	100	0	Inadequate or aging infrastructure resulted in increased water loss Increased maintenance costs due to a decrease in population and revenue and consequently more restricted payment programs and increased water shutoffs Drinking water quality issues Expected longer heat waves, higher number of hot days, and severe rainstorms become more frequent and intense due to climate change
Harrisburg, PA	HAR	Capital Region Water	special purpose unit of local gov	100	0	Aging infrastructure Water quality issues Expected higher number of hot days, and severe rainstorms become more frequent and intense due to climate change
Hartford, CT	HFD	Metropolitan District Commission	municipal corporation	100	0	Aging infrastructure Water quality issues Expected severe winter storms affecting critical infrastructure, more precipitation falling as rain instead of snow causing flooding, hotter and drier summers due to climate change
Indianapolis, IN	IND	Citizens Energy	public trust	84	16	Water stress in drought periods Inadequate infrastructure to address the demand in peak times Aging infrastructure Expected intensification of spring severe rainstorms and more severe summer droughts reducing river flows
Jacksonville, FL	JAX	Jacksonville Electric	community- owned utility	0	100	Water quality issues Vulnerability to hurricanes which may affect the water supply system and cause

Authority						water outages Expected higher number of hot days, sea level rise increasing the risk of coastal flooding due to climate change
Memphis, TN	MEM	Memphis Light, Gas, and Water	municipal water utility	0	100	Dependency only on one source of water. Water quality challenges of groundwater due to the possibility of breaches in the upper protective confining layer where it is missing or thin Water quality challenges due to the high rate of lead pipes within the system Expected higher number of hot days, more precipitation falling as rain instead of snow due to climate change
Phoenix, AZ	PHX	Phoenix Water Services Department	municipal water utility	97	3	Water stress due to the increase in population and demand due to climate change Dependency on interstate negotiations that may affect the amount of supply Expected higher number of hot days, severe droughts, and more frequent and severe wildfires
Providence, RI	PVD	Providence Water	municipal water utility, self-funded	100	0	Water supply stress Water quality issues Expected more severe droughts, sea level rise, less precipitation falling as snow, shorter winter and longer summers due to climate change
Sacramento, CA	SAC	Department of Utilities' Water Division	municipal water utility	80	20	Climate change and recurrent droughts Expected higher number of hot days, greater risk of catastrophic flooding, reduction of snowpack in the Sierra Nevada, and more extreme droughts due to climate change
San Jose, CA	SJC	San Jose Water	investor-owned public utility	50	50	Water stress due to the increase in population and demand Climate change and recurrent droughts Expected sea level rise, coastal erosion, saltwater contamination, reduction of snowpack in the Sierra Nevada, and higher risk of wildfires due to climate change
Santa Rosa, CA	STC	Water Department	municipal water utility	93	7	Potential water quality issues due to wildfire Climate change and recurrent droughts Expected higher risk of wildfires and more severe droughts due to climate change
Toledo, OH	TOL	Department of Public Utilities	municipal water utility	100	0	Inadequate or aging infrastructure Water quality issues Expected intensification of severe rainstorms, severe summer droughts, and degradation of water quality in Lake Erie due to climate change
Washington, DC	DC	DC Water	independent authority of district gov	100	0	Inadequate or aging infrastructure resulting in increased water loss Expected higher number of hot days, higher tides caused by sea level rise, and high flood risk due to climate change

Table 2. Description of the conditions and data sources.

Attribute	Abbre.	Variable		Details	Data source
Community attributes	Pov	Poverty		Percent of population below the poverty line for 2020	ACS
	Gini	Gini index		Gini index for 2020	Census
	Pop	Population growth		City population growth from 2010 to 2020	Census
Biophysical attributes	Sup	Water supply stress		Annual demand/annual supply for 2021	Utility websites; water management plans; Utility/City CAFRs
	Dem	Water demand		Average gallon per capita per day of water use	Utility websites; water management plans; Utility/City CAFRs
Infrastructural attributes	Inf	Infrastructure condition	Non-revenue water (Non-rev)	Percent of unbilled water	Utility websites; water management plans
			Water main breaks rate (Breaks)	Total number of water main breaks per 100 miles of water mains	Utility websites; water management plans
	Dens	System Size		Total miles of water mains/Service area population	Utility websites; water management plans; Utility/City CAFRs
	Dep	Depreciation of water system		Total depreciation/Total miles of water mains for 2021	Utility/City CAFRs
Institutional attributes	Cons	Conservation		Total Conservation score for 2017 (Vanderbilt Water Conservation Index)	Hess et al. (2017)
	OpR	Operating ratio		Annual revenue /expenditure for 2021	Utility/City CAFRs
	Deb	Debt service coverage ratio		(Operating revenue – total operating expenditure)/ (principal paid + interest paid on long-term debt) for 2021	Utility/City CAFRs
	Lia	Liability asset ratio		Total Liability/ Total asset for 2021	Utility/City CAFRs
	Inv	Total investment in the water system		Total investment in system 2021	Utility/City CIPs
Performance attributes	Out	Outcome	Drinking water quality	Highest level of reported water quality measures for 2021	Utility/City water quality reports
			Water affordability	Percent of income that goes to water bill for the lowest 20-percentile income group for 2021	Utility websites

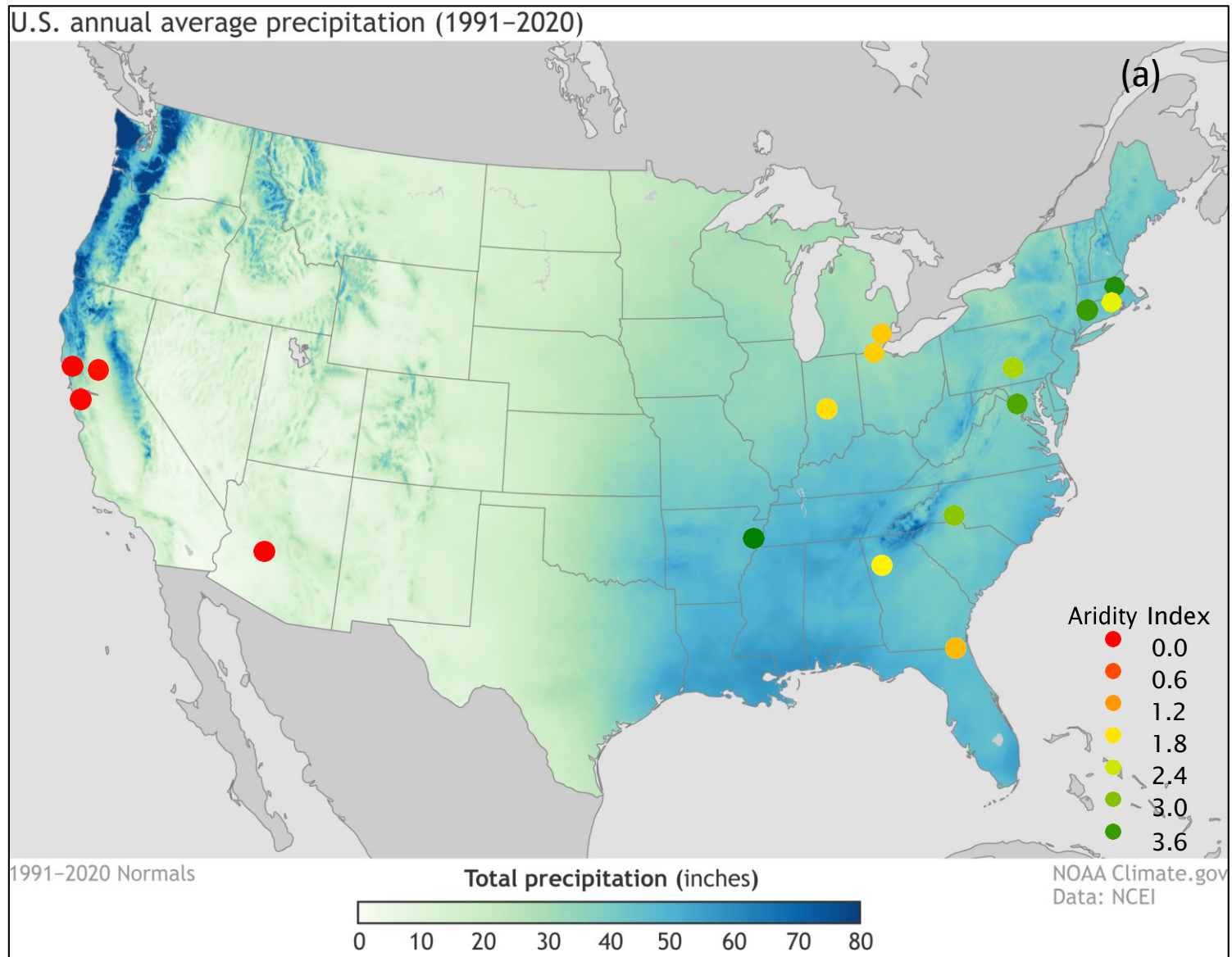
Note: CAFRS, Comprehensive Annual Financial report; CIP, Capital Improvement plans

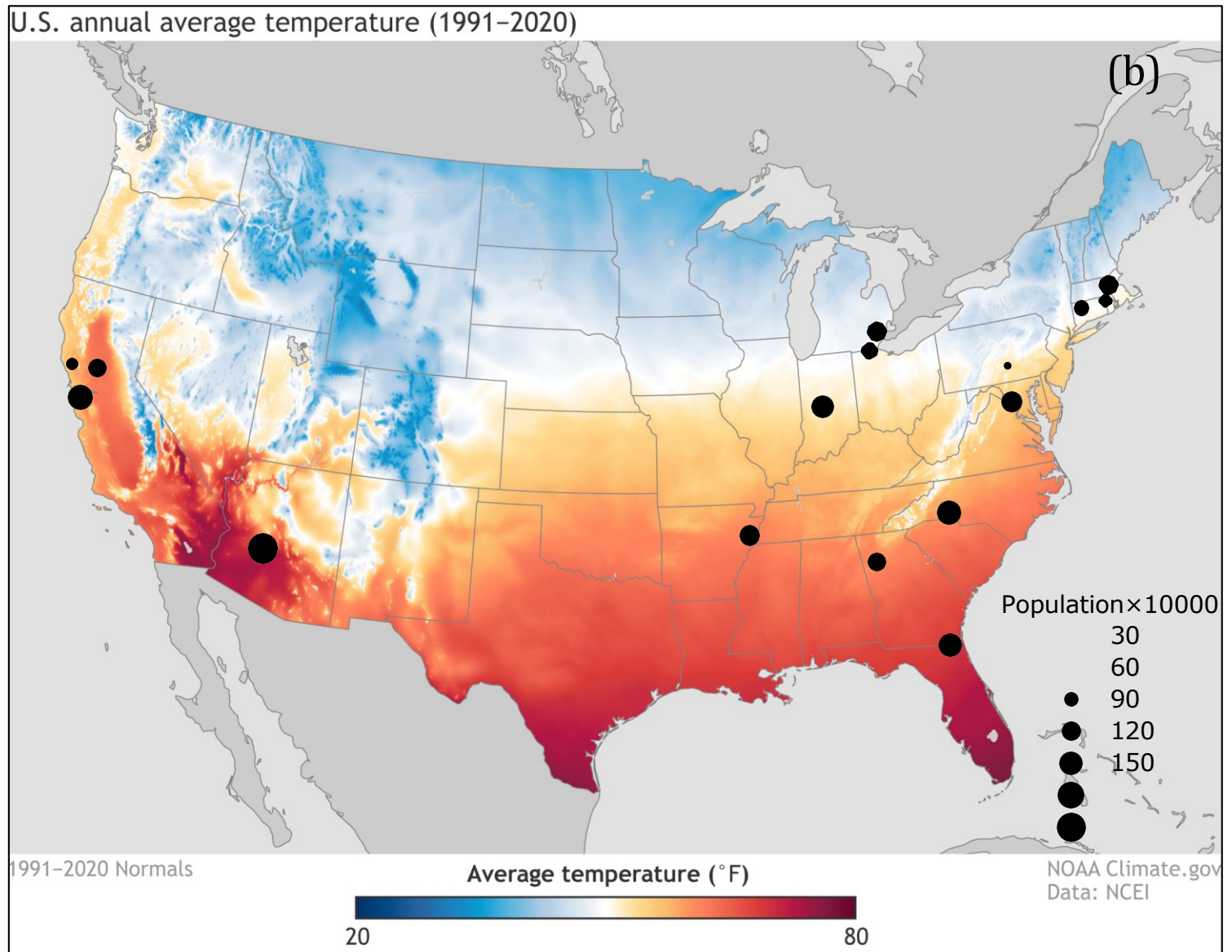
Table 3. Necessity and Sufficiency analysis.

Necessity analysis for high-AQ outcome			Sufficiency analysis			
Condition	Co	Cv	Configuration of conditions, high-AQ outcome		Co	Cv
			Condition present	Condition absent		
Pop	0.72	0.88	OpR, Lia, Dep, Deb	Pop, Gini, Pov, Sup, Dem, Cons, Dens, Inv, Inf	1	0.08
Gini	0.55	0.61	Pop, Pov, Sup, Dens, OpR, Dep	Gini, Dem, Cons, Lia, Inv, Deb, Inf	1	0.05
Pov	0.69	0.79	Pop, Pov, Sup, Dem, Cons, Dens, Lia, Deb, Inf	Gini, OpR, Inv, Dep	0.99	0.06
Sup	0.72	0.65	Pop, Gini, Pov, Sup, Cons, OpR, Lia, Dep, Deb	Dem, Dens, Inv, Inf	0.96	0.08
Dem	0.45	0.53	Pop, Gini, Pov, Sup, Cons, OpR, Lia, Inv	Dem, Dens, Dep, Deb, Inf	0.91	0.06
Cons	0.53	0.75	Pop, Gini, Pov, Sup, Dem, Lia, Dep	Cons, Dens, OpR, Inv, Deb, Inf	0.96	0.07
Dens	0.37	0.65	Pop, Gini, Pov, Sup, Dep	Dem, Cons, Dens, OpR, Lia, Inv, Deb, Inf	1.00	0.05
OpR	0.61	0.59	Pop, Gini, Pov, Sup, Cons, Dens, Lia, Dep, Deb	Dem, OpR, Inv, Inf	1.00	0.07
Lia	0.75	0.70	Pop, Dem, Dens, OpR, Lia, Inv, Deb	Gini, Pov, Sup, Cons, Dep, Inf	0.99	0.06
Inv	0.40	0.50	Pov, Sup, Dem, OpR, Lia, Inv, Deb	Pop, Gini, Cons, Dens, Dep, Inf	0.79	0.06
Dep	0.49	0.67	Configuration of conditions, low-AQ outcome		Co	Cv
Deb	0.58	0.64	Condition present	Condition absent		
Inf	0.70	0.78	Sup, Dem, OpR, Inf	Pop, Gini, Pov, Cons, Dens, Lia, Inv, Dep, Deb	0.92	0.09
			Sup, Dem, Lia, Inv, Dep, Deb	Pop, Gini, Pov, Cons, Dens, OpR, Inf	0.95	0.10
			Gini, Sup, Dem, OpR, Deb, Inf	Pop, Pov, Cons, Dens, Lia, Inv, Dep	1.00	0.09
			Dens, OpR, Inv, Dep	Pop, Gini, Pov, Sup, Dem, Cons, Lia, Deb, Inf	1.00	0.11
			Pov, Sup, Dem, Cons, Dens, OpR	Pop, Gini, Lia, Inv, Dep, Deb, Inf	0.78	0.10
			Pop*Gini*Pov*Cons *Lia*Inv*Deb*Inf	Sup, Dem, Dens, OpR, Dep	0.95	0.10

Table 4. Average number of conditions present, grouped by categorical attributes.

	Number of conditions present on average		Percent of conditions present in each attribute on average	
	Low-AQ	High-AQ	Low-AQ	High-AQ
Community	1	2.2	33.33	73.33
Biophysical	1.5	1.2	75.00	60.00
Institutional	1	1.5	33.33	50.00
Infrastructural	2.6	2.9	52.00	58.00
Total	6.1	7.8	-	





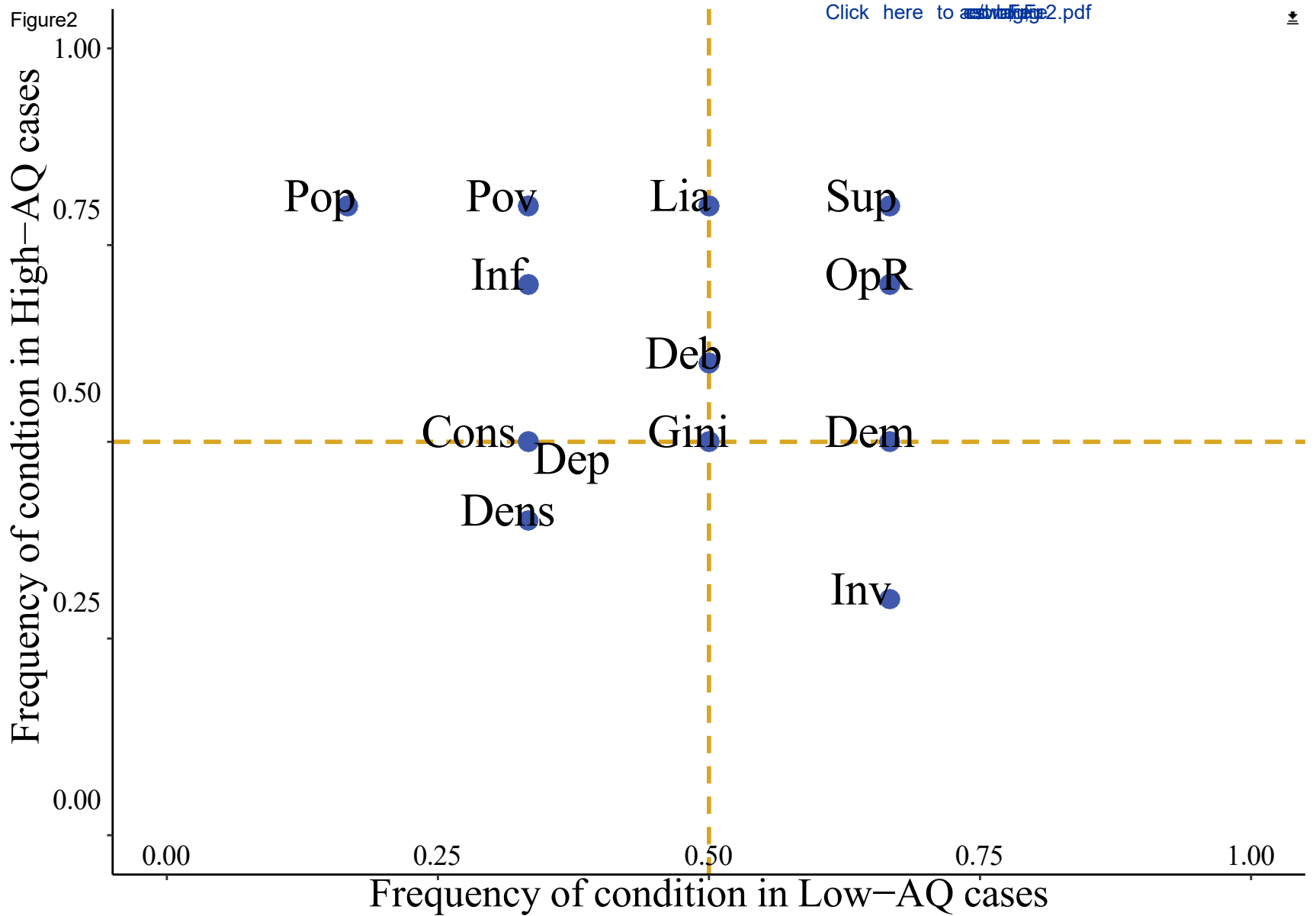


Figure 3

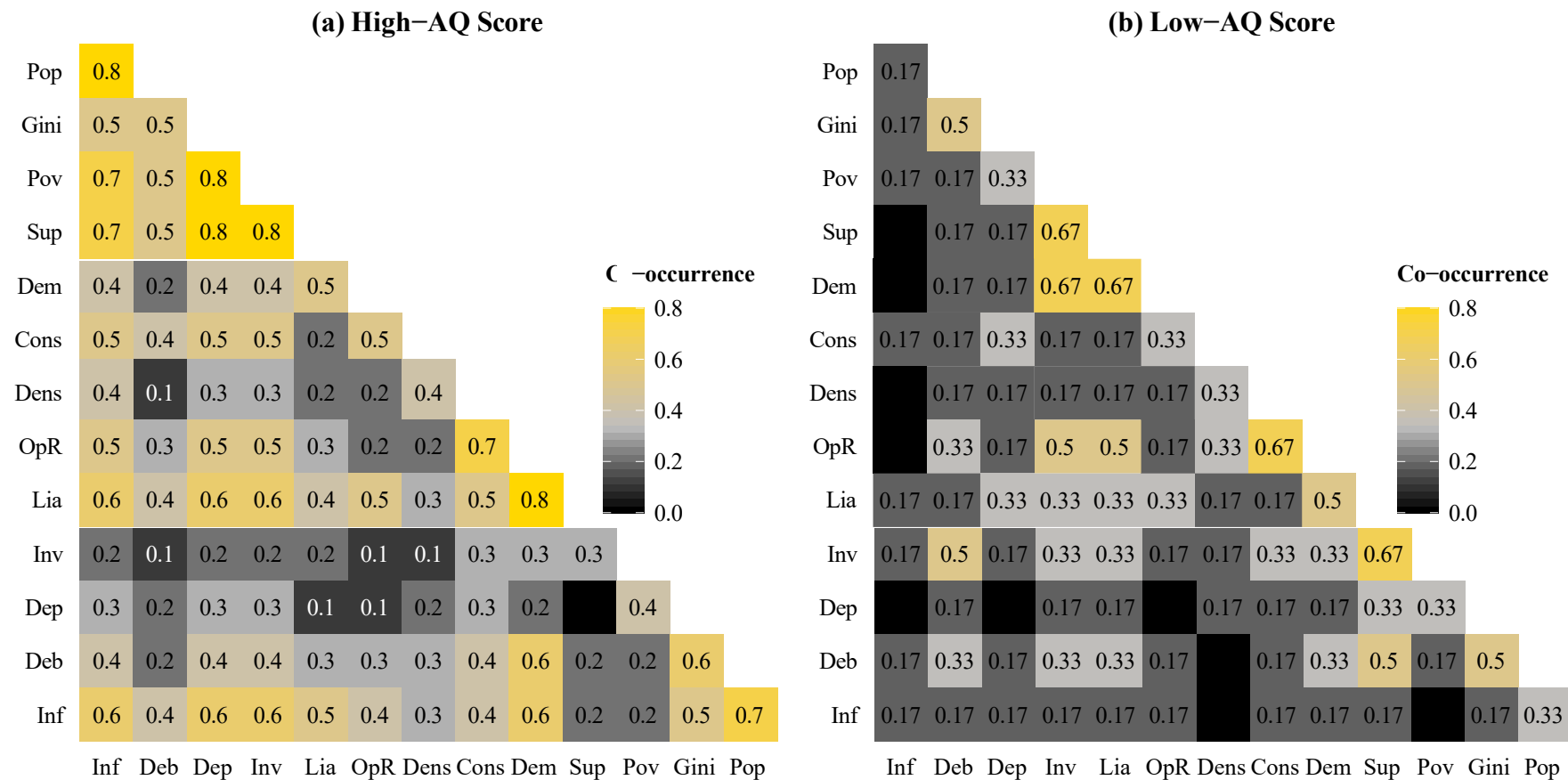


Figure 4

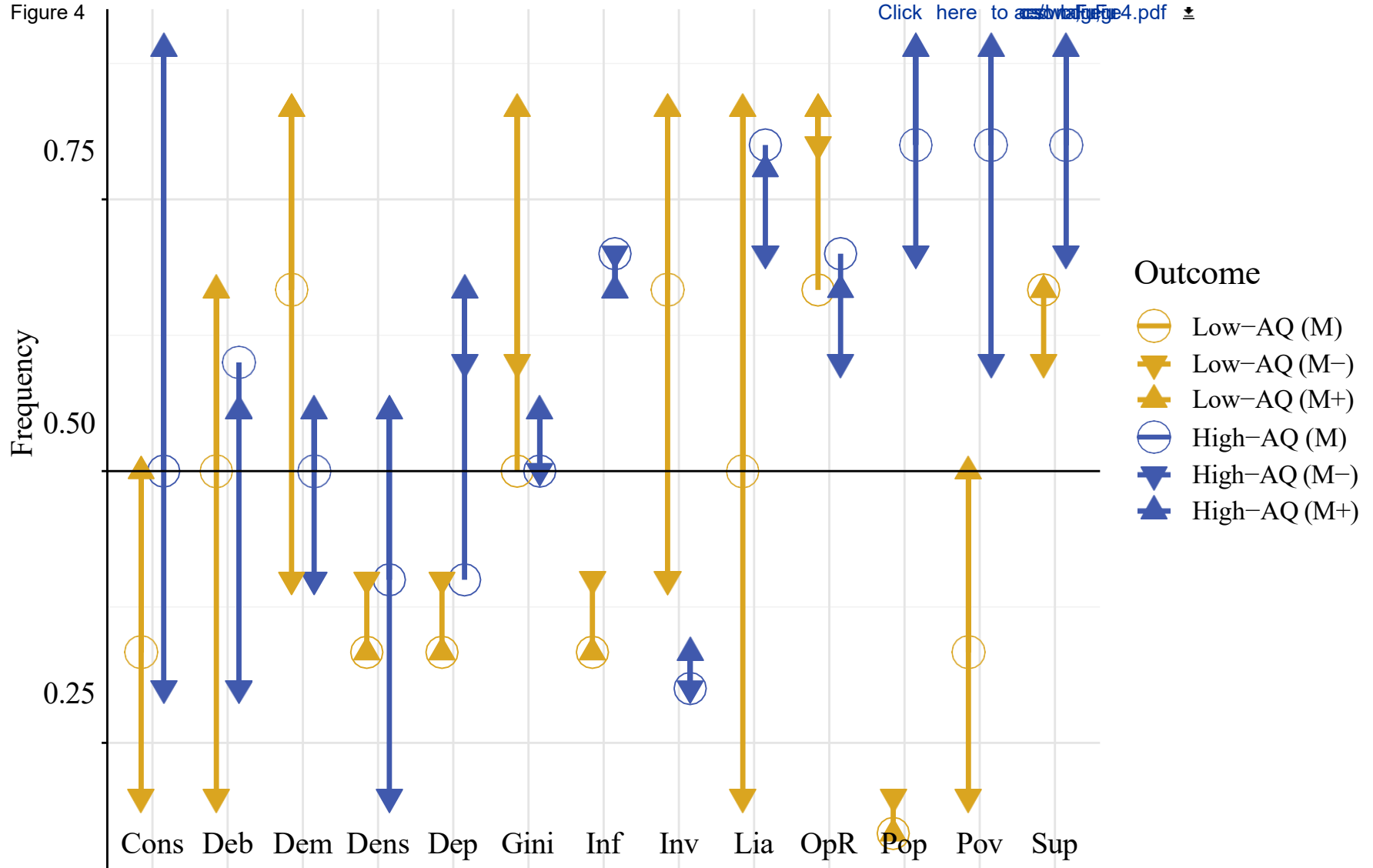


Figure 5

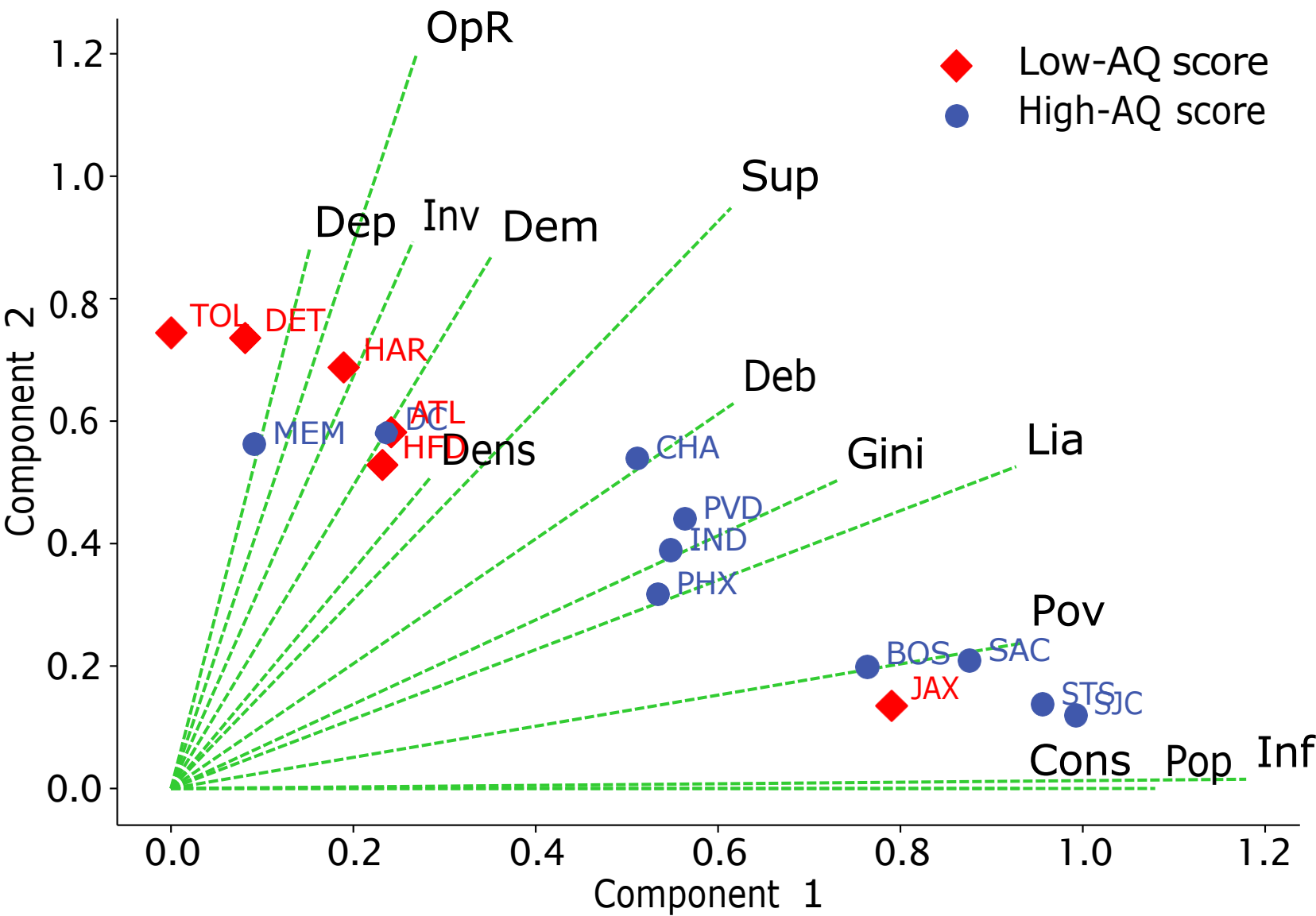


Fig. 1. Geographic locations and climate features of case studies: (a) Annual average precipitation (sourced from NOAA U.S. Climate Normals) and aridity index (sourced from Hess et al., 2017); (b) Annual average temperature (sourced from NOAA U.S. Climate Normals) and service area population (2021 utility reports).

Fig. 2. Frequency of conditions in association with AQ score. The figure depicts the frequency of occurrence of different conditions for the AQ scores based on their presence or absence in each outcome case. The figure has been divided into four quadrants based with a dashed line on a threshold that represents an equally likely occurrence of a condition in any outcome. The upper left and lower right quadrants represent conditions that are more present in high and low-AQ scores, respectively. The upper right quadrant displays conditions that are present in both outcomes, while the lower left quadrant depicts conditions that are mostly absent in either outcome.

Fig. 3. Co-occurrence of conditions: (a) high-AQ score cases; (b) low-AQ score cases. The color scale on the right indicates the frequency of co-occurrence, ranging from 0 (never co-occur) to 1 (always co-occur). Conditions tend to co-occur in groups, suggesting they do not contribute to the outcome in isolation. Moreover, some groups of conditions co-occur more frequently in cases of high-AQ scores, while they are almost absent in low-AQ score cases. The diagonal represents the prevalence of that specific condition.

Fig. 4. Frequency variability of the conditions based on the sensitivity of defined thresholds. Each condition is represented by two lines: a blue line indicating a high-AQ score outcome and a red line indicating a low-AQ score outcome. The lines consist of three points each (points might overlap), which mark the boundaries of variability corresponding to the frequency of each condition in each of the three scenarios (M, M-, and M+).

Fig. 5. Non-negative matrix factorization on conditions and cases using two components. The green lines represent conditions in the two-dimensional space based on the vectors that indicate the component weights and points represent cases.