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Developing a Drought Resilience Matrix to Evaluate Water Supply Alternatives

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Abstract: Cities around the world are facing increased sensitivity to drought effects. Climate-change-induced drought affects not only the natural hydrology of the broad macroclimate but also those in the urban microclimates. The increasing frequency and duration of droughts are creating challenges for urban water utilities to convey water through distribution systems to customers reliably and consistently. This has led many urban areas like San Francisco, California, to search for unique alternative water supply projects to help bolster the drought resilience of the coupled human and natural water system. This paper focuses on applying the features of resilience (i.e., plan, adapt, absorb, and recover) through a drought resilience matrix to water supply alternatives to analyze how the addition of these projects would increase the overall water system's drought resilience. San Francisco, California, was used as the case study to test the use of this matrix. Three portfolios (modifying existing supply, recycling, and desalination, as well as local approaches) were created and tested in the matrix. Each portfolio is composed of various alternative water supply projects that the San Francisco Public Utilities Commission (SFPUC) is considering for implementation. Results concluded that the local approaches portfolio provided the most drought resilience, with the recycling and desalination portfolio providing the least resilience. The study approach and the presented findings will provide guidance to water utility professionals in supply planning to enhance drought resilience.

Keywords: drought; resilience; water supply system; WEAP

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1. Introduction

Cities are increasingly becoming more vulnerable to inside and outside stressors. Two of the major stressors affecting cities around the United States are climate change and increased urbanization. With the rapid increase in greenhouse gas emissions (GHGs), many areas around the world are warming significantly, with adverse effects being seen in both the human and natural water systems [1]. It is also predicted that roughly 86% of the developed world will be urban by 2050. Urban settings play a vital role in inflaming the effects of climate change. While the extent of this contribution to climate change varies from city to city, some commonalities in underlying urban dynamics exist. Increased urbanization paired with climate change creates unique challenges for water infrastructures and resources that lead to the degradation of water distribution systems with an increase in nutrient and pollutant water quality issues [2,3].

In order to combat these issues, urban areas are growing a broad array of approaches to help plan the incorporation of sustainability into planning their water resources. One of the approaches that have emerged in growing importance is the use of resilience and adaptive management. Resilience is not a new concept, but the term has been reimagined and redefined in multiple ways to capture the complexity of a specific problem and altered solutions. In order to understand the impacts of climate change and population growth on the urban water sector, it is essential to have a definition that can factor in all facets of the urban environment. It is also important to understand how climate change or increased urbanization will affect an area (i.e., more droughts, floods, less precipitation, warmer temperatures, etc.). For the purposes of this study, we will be employing the use of drought resilience and urban resilience definitions [4].

The best definition of urban resilience that captures the components of the urban water sector holistically is the one given by [5]:

> *Urban resilience refers to the ability of an urban system and all its constituent socioecological and sociotechnical networks across temporal and spatial scales to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and quickly transform systems that limit current or future adaptive capacity.*

Urban resilience factors in the ability of systems under stress to maintain key functionalities and to reduce the risks associated with disasters and hazards like droughts and increased temperatures [6]. Treating cities more as highly functional urban networks that are connected to the environment helps to produce more focused approaches on how to help increase the urban areas' adaptive capacity. For the urban water sector, the two key functionalities that would be essential to maintain during droughts are the ability of the system to meet the minimum demand and provide flows to the environment reliably and consistently. Very few efforts have been made to recognize and incorporate various adaptation measures to increase the resilience of urban environments and the water bodies they depend on for supply from climate change [7,8].

The term drought resilience, as defined by the University of California, Davis Sustainability Group as "the maximum severity of drought during which core water demands can still be met, including social and minimum environmental requirements" will also be used. Drought resilience offers a buffer for urban areas and their regional water system that face increased droughts in the face of climate change.

The literature suggests that not many frameworks or tools exist that are able to measure the resilience of the urban water system [9]. Some studies have looked at drought resilience on a household scale, and even fewer studies have looked at measuring and assessing the drought resilience of an urban water system [10]. No studies could be found on using the concept of drought resilience to understand which combination of water supply alternatives would act as the best buffers for the natural water system. In order to better equip urban areas that suffer from drought, we created a drought resilience matrix that operates off the definitions of drought resilience and urban resilience mentioned earlier. The drought resilience matrix is designed to view resilience from the perspective of a "safe-to-fail" mentality. The "safe-to-fail" mentality focuses on anticipating different system failures and designing the system in a way that allows the failures of the system to have minimal impact while keeping primary functions intact [11].

The proposed matrix focuses on identifying which of the water supply alternatives will enable the water supply system to become more resilient against long drought periods, allowing the system to fail successfully during droughts in ways that do not compromise its ability to convey water to customers. Some elements of redundancy are also analyzed by using this matrix, as the incorporation of such a concept is said to help spread the risk across systems through space and time [11].

Also, droughts have social implications, causing disruptions in water supply distribution that may result in water use reductions for residents, reallocations of water, and increased pricing for high water usage [12]. Not all communities are affected the same by droughts, with some residential areas being more vulnerable to water shortages than others. Studies suggest that the socioeconomic status of urban environments can be advantageous in detecting the level of resilience present in human systems against hydro-logical impacts [13–15].

Many modeling systems and frameworks that seek to assess these water supply alternatives are not able to adequately account for social and political implications, leaving a gap in the creation of effective management plans for drought resilience. Here, we seek to fill in the gap by developing a tool that can incorporate and assess social considerations with environmental, economic, institutional, and political considerations to determine if a set of water supply alternatives will help to buffer the urban water system from the effects of drought increasing the water supplies' ability to be drought resilient.

This framework is aimed at helping managers make more informed decisions when choosing which water supply alternatives to add to the urban water system in order to increase the system's overall drought resilience. While we believe this matrix could be employed for use in any urban area that suffers from droughts or is expecting an increase in dry years, we chose San Francisco, California, and its Regional Water System as the case study to test the effectiveness of the proposed matrix. Recent studies have highlighted the importance of addressing vulnerability, resilience, and equity in urban planning processes [16]. Additionally, disaster resilience has been identified as a critical factor in increasing the score of urban areas' resilience against various hazards [17].

2. Study Area

San Francisco is the largest metropolitan area of northern California, with an estimated population of 815,201 (US Census Bureau, 2021,https://www.census.gov/quickfacts/fact/table/sanfranciscocountycalifornia (accessed on 1 July 2023)). San Francisco Public Utilities Commission (SFPUC) is the water utility that services San Francisco and conveys water from the Regional Water System in the Central Valley to San Francisco residents and wholesale customers. SFPUC also governs wastewater and drinking water treatment in addition to providing power in various forms for their customers [18]. The Regional Water System depends on water surface flows from the Tuolumne River, Alameda, and Peninsula watersheds. The Tuolumne River is the main river that the Regional Water System depends on, as it receives snow-melt from the Sierra Nevada and transfers a portion of that to Hetch Hetchy Reservoir (Figure 1).

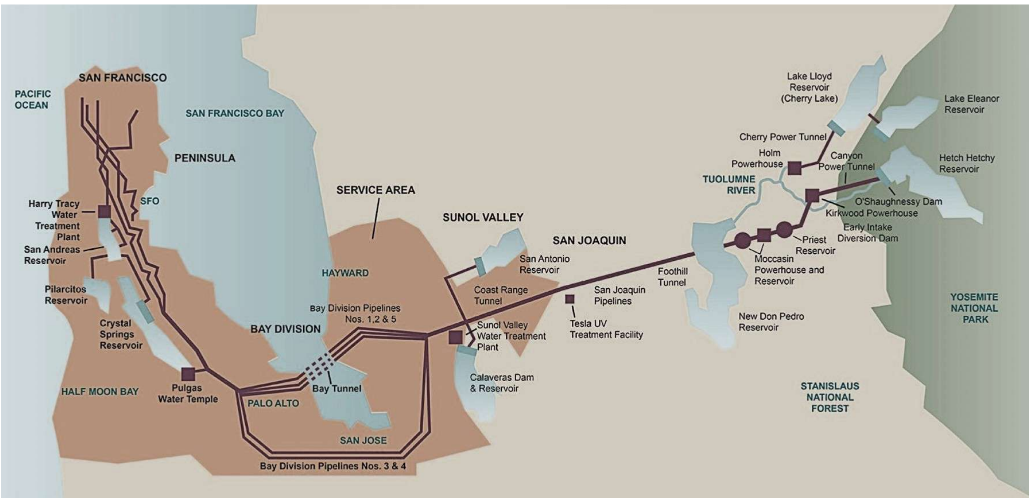

Figure 1. The regional water system configuration of San Francisco Public Water Utility Commission.

San Francisco's water infrastructure and watersheds are subject to changes caused by climate change effects in the form of increased temperatures, seasonal pattern shifts, and increased drought. For San Francisco, the increased occurrence of droughts is an area of concern. Climate studies predict that the Sierra Nevada snowpack that San Francisco's Regional Water System depends on will decline by 80% near the end of the latter century [19]. New insights were gained from the 1976–1977 and 1987–1992 droughts that reinforced the need for San Francisco to diversify its surface water supplies and facilitate more investments being made into drought resilience measures [12].

San Francisco has employed strategies before to combat drought resilience after the two significant drought year periods mentioned earlier, but suppliers' effects fell short as their implemented strategies were tested during the five-year drought that started in 2012. SFPUC's methods to achieve drought resilience through bolstering water planning requirements, increasing water trading availability during shortage periods, and increasing financial assets were found to be inadequate in providing drought resilience for water supplies during the 2012–2016 drought [12]. The problem that occurred was, in fact, that SFPUC had not included long-term drought resilience measures in their planning, but instead focused on short-term measures. Extreme conservation measures had to be forced in 2015 during the drought because of the severity of the drought's effects on the water supply. While this helped San Francisco through the tail end of the drought, it produced issues on the level of local authorities versus state authorities. When the state of California enforced urban water conservation during the 2015 drought, it caused tension between the state and local authorities as historically local authorities made judgment calls [12]. That is why it is important to incorporate institutional changes and arrangements on a local and statewide scale into drought resilience strategies because better development and communication between governance structures can lead to the promotion of adaptation to climate change [6].

3. Methodology

To create the drought resilience matrix, we first had to identify which areas of water systems were the most vulnerable based on how they had responded to previous droughts. Five main areas were identified and adapted from [12]:

1. Creating and coordinating water shortage contingency planning on the local and state levels: For San Francisco, this is one of the most important improvements that could be made to bolster drought resilience after the 2012–2016 drought, where state and local authorities did not entirely agree on the steps that should be taken to ensure the conservation of the water supply.
2. Encouraging water system flexibility and integration: This area mainly focuses on increasing the state and local investments focused into integrated regional supply management. The additions of innovative water supply projects and regulatory planning and investments are encouraged.
3. Elevating water suppliers' financial resilience: Utilities can increase their ability to recover and adapt to droughts through a method of instituting drought pricing with their customers. The state can provide more partnership opportunities by helping local water utilities to factor in constitutional water pricing with flexibility.
4. Addressing water shortages in vulnerable ecosystems and communities of people: Understanding how saving water supply in the urban, city-like, areas should inform planners and managers more about how these savings will affect outside communities like the rural areas. Some rural areas that depend on wells may experience shortages during droughts that are largely affecting city supplies. Vulnerable communities in the environment must be identified, and water shortages that affect them need to be planned for.
5. Creating more long-term plans for water use efficiency and drought resilience: In order to plan for future benefits from long-term conservation effects, planners and managers must find ways to limit the reduction of water used primarily on urban landscapes or balance it out by allocating more water to long-term savings or creating a better way to store water that allows for reliability during droughts.

After these areas were identified, it was important to then acknowledge the stakeholders involved in fostering this drought resilience. For California, state entities that oversee policies and arrangements made in relation to the urban water systems include the California Public Utilities Commission, the Department of Water Resources, and the State Water Board. Some of these agencies help to provide funding sources for local water projects.

Once relevant governmental entities are discovered and included, the next step is to focus on the problem in its current condition. For places like San Francisco, the urban area uses 10% or more of the state water supply, and almost half of that is used for irrigation purposes [12]. The share of water used as environmental flows is okay, but it depends heavily on surface water flows, which during drought years would be much lower, affecting water available for aquatic and nonaquatic habitats.

We then identified the three major goals and strategies used to incorporate drought resilience into urban water management. The first goal is to shift the focus on management strategies to allow minimal disruptions to occur during droughts that draw down the natural environment's ability to function as well as the impacts on the social and economic structures in the urban environment. The second goal is to incorporate more supply investments to reduce the impact of water shortages like new storage for supplies. The third goal is to increase the use of more demand-side management measures. These measures usually include some water use reductions/restrictions or water pricing increases for those that go past a certain level of use to incentivize them to use less. These demand strategies must be both long-term and short-term procedures for reducing water use.

Three portfolios of water supply projects for San Francisco are then created based on these goals and strategies. Each portfolio includes a range of water supply alternatives that are proposed by SFPUC as additions to the Regional Water System. Not all potential water supply projects being considered by SFPUC were tested or discussed in this paper. Only the alternatives that produced at least one MGD of water for the SFPUC customers are considered and are as follows: conservation techniques, additional Tuolumne River diversions, Los Vaqueros reservoir expansion, Bay Area Regional Desalination Plant (BARDP), West-Side Enhanced Water Recycling Plant, Daly City Water Recycling Plant Expansion, East-Side Enhanced Water Recycling Plant, and In-City Desalination Plant. The alternative water supply projects with their associated yields and costs are described in (Table 1).

These water supply alternatives were grouped into three diversified portfolios. The portfolios were assembled based on an effort to combine different centralized versus decentralized strategies. The portfolios were also arranged in a way where cost, quantity, construction/implementation time, and proximity to San Francisco were considered. Some portfolios have projects that are more collaborative on a regional level, while others have projects that focus solely on the SFPUC municipality and its immediate customer base. Different projects offer different levels of environmental impacts that were also considered when they were created.

Modifying Existing Supply, or Portfolio A, contains the Los Vaqueros reservoir expansion, Tuolumne River diversions, and conservation technique projects. The projects in Portfolio A focus on combining small-scale additions that would be implanted in the existing infrastructure of current practices, making the cost of each project more affordable. Portfolio A resulted in being the most cost-effective portfolio, at USD 3024 per acre-foot, that SFPUC could choose.

Recycling and Desalination, or Portfolio B, is composed of the Bay Area Regional Desalination Plant, the East-Side and West-Side Recycled Water Project, and the Daly City Project. Portfolio B was observed as the most expensive, containing the larger projects that require newly constructed pipes, underground reservoirs, treatment facilities, and collaboration with a network of other agencies. Portfolio B focused on the use of recycled treatment plants as an additional water source. This portfolio also looked at the increasing SFPUC's communication and collaboration with other water agencies and districts to foster a sharing of information and innovative ideas. The Bay Area Regional Desalination Plant is a project that requires a significant amount of collaboration, and this could add resiliency to the Regional Water System by having institutions share a resource and potentially build water resources together, coming up with more holistic and innovative solutions. However, portfolio B came with the lowest yield, of 20.4 MGD, and the highest cost, of USD 18,039 per acre-foot, making it a less-than-ideal portfolio of choice from a cost–yield perspective (Figure 2).

Local Approaches, or Portfolio C, contained the East-Side Recycled Water Project, the In-City Desalination, and the conservation techniques. This portfolio was designed with a focus on more local solutions. As shown in Figure 3, Portfolio C was very close concerning yield (54 MGD) to Portfolio A, but in terms of cost, it was more expensive, at USD 7049 per acre-foot, than A, but less expensive than B (Figure 2).

The cost and yield of each alternative water supply project individually are shown in Figure 4.

Also, the cost and yield of all three portfolios are shown in Figures 2 and 3, respectively.

The drought resilience matrix applies the four main features of resilience (i.e., plan, adapt, absorb, recover), to water supply alternatives to evaluate which additional projects will increase the drought resilience of the existing water distribution system. These four resilience features were redefined to incorporate more characteristics intrinsic to the functionality and management of urban water systems. Each feature has an associated score that correlates to the level of importance the feature holds in increasing drought resilience. After each portfolio of water supply alternatives is judged and scored based on its ability to fulfill the components associated with the four resilience feature definitions, the total score is added up to 55 points.

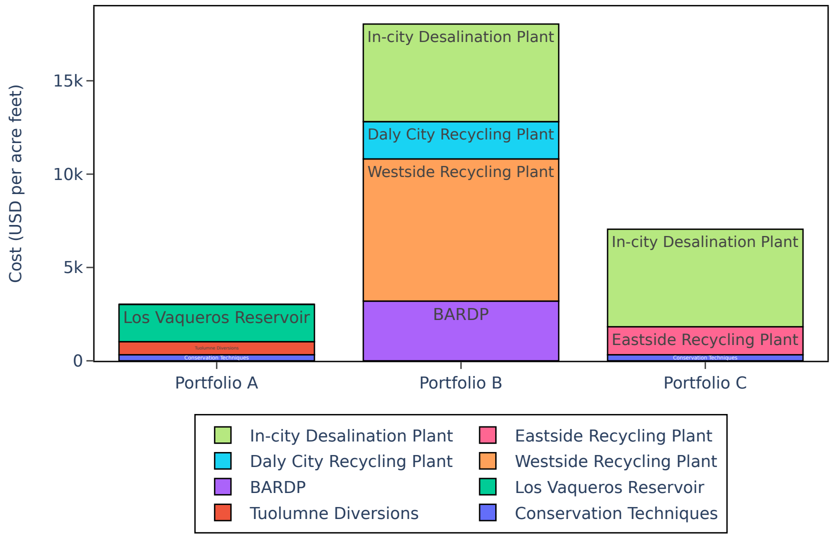

Figure 2. Three potential portfolios composed of a combination of different alternative water projects with the portfolios' associated cost.

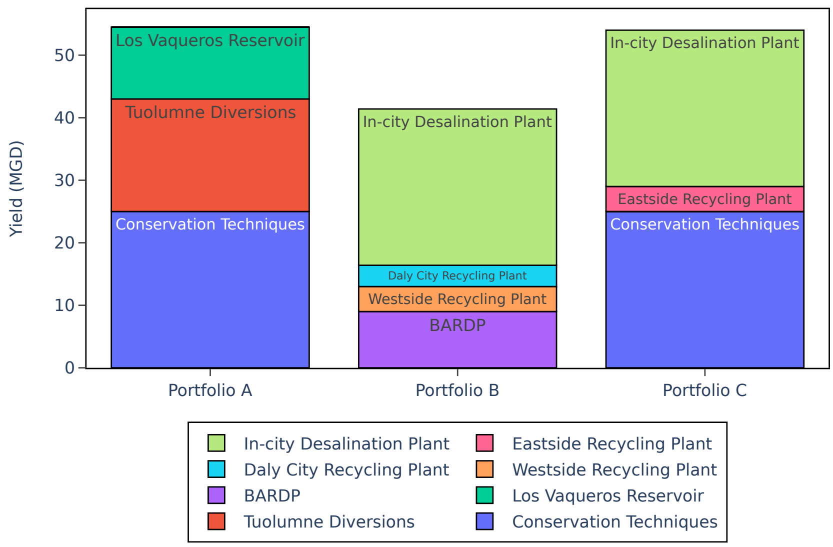

Figure 3. Three potential portfolios composed of a combination of different alternative water projects with the portfolios' associated yield.

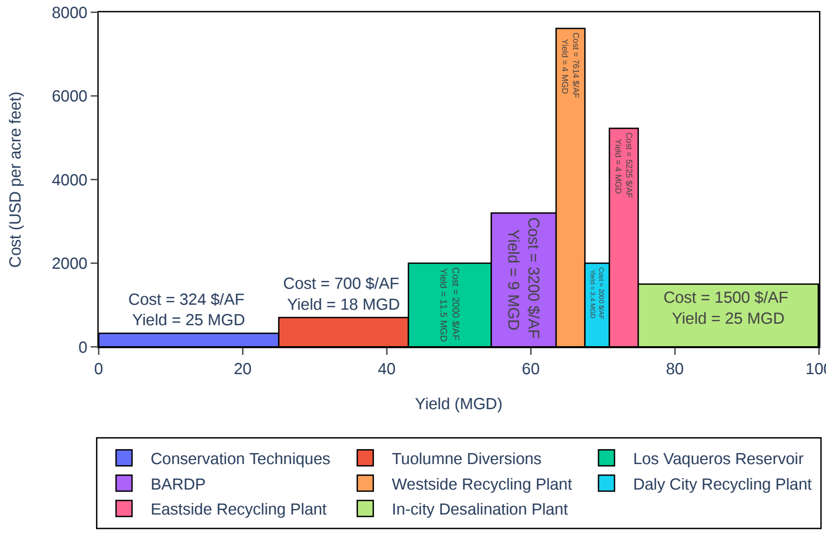

Figure 4. The yield and cost for each alternative water supply project.

Table 1. San Francisco Public Utilities Commission's alternative water supply projects expected project yields (MGD), and associated portfolios [20].

Water Supply Alternatives/Projects	Project Description	Project Yield (MGD)	Project Cost (USD/ Acre-Feet)	Associated Portfolio(s)
Conservation Techniques	Includes techniques such as rainwater harvesting, potable reuse, high-efficiency fixtures, rebates, etc., to be used in drought and nondrought years.	25	324	Modifying existing supply, local approaches.
Additional Tuolumne River Diversions	Diverting additional water from Tuolumne River (past current 265 MGD limit) due to annual deliveries being increased to 290 MGD. Water is used as drinking water in nondrought years.	18	700	Modifying existing supply.
Los Vaqueros Reservoir Expansion *	Increasing reservoir capacity from 160,000 AF to 275,000 AF. This reservoir may also be used during drought years to store water from BARDP.	11.5	2000	Modifying existing supply.
Bay Area Regional Desalination Plant (BARDP)	A multi-water agency desalination project that seeks to turn brackish water into drinking water for SFPUC customers for use in drought and nondrought years.	9	3200	Recycling and desalination.
West-Side Enhanced Water Recycling Plant	Recycling wastewater effluent from Oceanside Water Pollution Control Plant to be used for nonpotable water purposes (i.e., irrigation) in drought and nondrought years.	4	7614	Recycling and desalination.
Daly City Water Recycling Plant Expansion	Increasing the capacity of the existing recycled water plant to offset current groundwater use for SFPUC wholesale customers in drought and nondrought years.	3.4	2000	Recycling and desalination.
East-Side Enhanced Water Recycling Plant	Recycling wastewater effluent from Southeast Water Pollution Control Plant to be used for nonpotable water purposes (i.e., irrigation, commercial, industrial, and toilet flushing) in drought and nondrought years.	4	5225	Recycling and desalination, local approaches.
In-City Desalination Plant	Constructing a desalination plant in San Francisco that treats seawater from the Pacific Ocean to service local SFPUC wholesale and retail customers drinking water needs in drought and nondrought years.	25	1500	Local approaches.

* Los Vaqueros Reservoir is an off-stream reservoir that was originally built by Contra Costa Water District (CCWD), one of San Francisco's largest regional water agencies.

3.1. Measuring Resilience: Plan, Absorb, Recover, and Adapt

Drought resilience in this paper consists of four metrics of planning, absorbing, recovery, and adaptability. Each of the four metrics was chosen as a measurable characteristic of resilience that is a major area of importance for drought resilience. Each of the four metrics is assigned a score based on their level of importance and difficulty in providing drought resilience. The portfolios are assessed using the drought resilience matrix for these four metrics, and an overall score is calculated for each portfolio. The portfolio with the highest overall score out of 55 points is the one that will provide the Regional Water System with the most drought resilience.

A description of each metric and the associated factors that each portfolio of options is scored on, as well as the breakdown for the scoring, can be seen in (Table 2).

Table 2. Assumptions and descriptions of drought resilience metrics (partially adapted from the National Academy of Science definition of resilience and [21].

Metric (NAS Resilience Features)	Description	Associated Factors	Possible Score (Out of 55 Points)	Score Breakdown (Per Associated Factor)
Plan	Focuses on the critical water distribution system functions (conveyance of water to customers).	Institutional aspects Water distribution system reliability Cost Water yield Implementation Time Project location	10	2 2 2 2 1 1
Absorb	Focuses on thresholds, positive and negative feedback, intrinsic threshold of water supply alternatives to disturbance.	Redundancy Drought frequency threshold Demand site coverage Supply stress [a]	15	3 4 5 3
Recover	Focuses on time and scale of drought disturbance and how long the performance of the urban water system is degraded.	Degradation time (years) Max water supply degraded Supply diversity [b]	20	7 8 5
Adapt	Focuses on adaptive management and reorganization of water distribution system after drought. Re-evaluating or redefining plans, policies, and approaches.	Capacity augmentation [c] Diversity of structures sizes Connectivity to Regional Water System	10	5 2 3

[a,b,c] Terms/concepts adapted from the [22] that focused on quantitative metrics used in Bay Area Water Supply and conservation resilience assessment. The characteristics of these terms were altered for this study.

The development of each metric will be discussed below:

- *Plan Metrics*

The planning feature of resilience focuses on the institutional aspects of resilience as well as the ability of the physical infrastructure to provide its water supply services reliably and efficiently [21]. The total score a portfolio could achieve for this metric is 10 points. These points were allocated to portfolios based on a series of associated factors like consideration of cost, water yield, implementation time, and location of proposed projects in portfolios. The portfolio containing the water supply alternatives that collectively have the highest yield, shortest implementation times, lowest cost, and will be geographically close to San Francisco received higher scores for this metric than their counterparts.

The planning metric seeks to address the uncertainties of drought occurrences and magnitudes, rating more highly those water supply options that have a higher yield and are spatially closer to the SFPUC customers, as it helps fortify the reliability of the water supply by having closer access to more water.

The implementation time and project location were factors that were weighed less heavily for this metric (Table 1) with an associated score of 1 each because they have smaller trade-offs than some of the other factors. Project implementation time is variable and can change depending on permitting budget considerations and weather. Therefore, while it is something that is an important part of the planning process, the drought resilience of the overall Regional Water System will not be as affected as it would be by a smaller water yield or low reliability. Project location receives similar point valuation as decentralized and centralized approaches to location come with pros and cons but does not ultimately affect the drought resilience of the Regional Water System dramatically. The geographically closer projects will have a quicker response and distribution time than those farther away, but out of the factors considered, it is not one of the weightier matters. Addressing how the interconnectivity of the urban water system can be improved will increase the drought resilience of the overall network [23].

- *Absorb Metrics*

The absorb metric focuses on the use of thresholds that are intrinsic to the water supply system and additional water supply alternatives. This metric encompasses the ability of the alternative water system to endure stress and the sensitivity of the system's functions based on the level of their exposure to drought variables [21].

This metric is worth 15 points and each portfolio's water supply alternatives are scored on factors like the threshold for drought frequency, redundancy, supply stress, etc. The associated factor supply stress is an idea adopted from [22] that sought to use supply stress as an indicator for assessing the fraction of allocations from the San Francisco Regional Water System that is currently being used.

Ref. [22] were looking at assessing the resilience of the Bay Area Water Supply and Conservation Agency (BAWSCA), the 26 water agencies that are the wholesale customers of San Francisco Public Utilities Commission (SFPUC), which depends on SFPUC's Regional Water System. Each of these wholesale customers has an individual supply guarantee for the water delivery amount each wholesale customer is entitled to. Those water agencies that do not have individual supply guarantees were considered more supply-stressed than the other water agencies. For the sake of this study, the concept of supply stress is altered to identify which portfolios were able to alleviate the stress of the Hetch Hetchy reservoir water supply, thus allowing for more of that water to be preserved or potentially used in the future as individual supply guarantees for those water agencies that need it. The focus for this metric is also on the portfolio's intrinsic reliability based on the shortcomings of demand vs. delivery during the projected project period. This seeks to determine which portfolio or individual alternative water sources combined with the existing Regional Water System allow one to limit rationing to 20% system-wide reductions during droughts. Each portfolio is also assessed for the level of redundancy they would provide to the regional water system as a whole.

This metric is weighted more in total possible points than the plan or adapt metric because absorbing is a concept of resilience that is regarded more highly as an integral component by system managers, planners, and decision-makers as the area of absorption are critical to ensure important societal systems and processes are sustained through known and new threats [21]. The absorb feature is characterized by thresholds as well, and one of the best ways to increase the strength of resilience in the urban environment is by acknowledging these thresholds and feedback. For drought resilience, effectively spreading out a failure if one should occur and understanding the frequency of drought these portfolios can bear and how much of the demand each portfolio can cover is more imperative because it shows which portfolios are going to aid the Regional Water System in providing more longevity for the supply of water to be delivered to customers during extreme drought periods.

- *Recovery Metrics*

The recovery feature of resilience focuses on the time and scale of disturbances like drought and how long the performance of the urban water system is degraded [21]. The total points assigned to this metric are 20. Recovery is assigned a larger point valuation because it is a resilience feature that characterizes systems that can move from a "fail-safe" mindset in urban areas to a "safe-to-fail" mindset. The recovery feature provides important information about how far an urban water system can be pushed before it exceeds the desired threshold and helps one determine what alternative water supply projects may help to increase the elasticity of this threshold. The disturbance timing (and the magnitude and frequency of the disturbance) can determine a lot in terms of how the state of the water system may react and how it will impact the system performance and functioning [21].

One of the most important parts of the urban water system is its ability to deliver water safely and reliably to its customers. Any time that is interrupted, not only do the customers suffer from a lack of water supply, but the economy suffers. Millions of dollars are poured into the operation and maintenance of these large treatment and conveyance systems, so knowing how well these proposed water supply alternatives will aid the urban water system in recovery from drought is paramount, making it a weightier issue. The portfolios were assessed for associated factors like degradation time, supply diversity, and the maximum amount of water supply that was degraded over the extreme drought scenario. The portfolio that can bring the system functions back (i.e., meeting the demand and restoring diminished reservoir levels and river stream flow) was given a higher score. Factors of the amount of time it takes for each alternative water supply system and portfolio to recover from drought periods were assessed using this metric. Also, the quantity of water recovered by each alternative water supply was considered. The supply-diversity-associated factor is another term that is adapted from the study of [22], where most of the BAWSCA agencies depend on SFPUC for water supplies while the others have varying sources (i.e., imported water, recycled water, groundwater, etc.) that they obtain their water supply from. The agencies with more diversified water supply sources will be able to combat future droughts better as they will have options to choose from that allow their demands to still be met reliably and resiliently, stepping back from those sources that are jeopardized and shared with others. With the uncertain future of the water supply reliability for both SFPUC and many BAWSCA agencies, and the expected economic losses due to water supply variability from interruption of flow through drought, it is important to diversify the type of water supply alternatives that are available [22]. To measure the potential reliability of the regional water system with the addition of these portfolios, all portfolios are tested to see which one offered the most diversity in water supply types and which of those portfolios contained the most water supply alternatives that could be used in both drought and nondrought years. This shows which portfolios offer the most consistent diversified water supply options.

- *Adapt Metrics*

The adaptation metric seeks to assess the ability of water supply alternatives in the portfolios to enhance the drought resilience of the water system through measures that allow for greater mitigation. Adaptation acknowledges that the change will occur (i.e., there will be more droughts) and seeks to assess the infrastructures' ability to last through the disturbance and reduce the vulnerability of the water system to major draw-downs. This metric focuses on actions that can be taken to reduce the impacts of the event of droughts and to anticipate the changes that will be made to the infrastructure and counteracting them with measures that will support the persistence of the system through drought [9,24]. The form of the urban environment and its ability to accommodate different alternative water supply structures are factored into this metric's score as well. The qualities of urban design and form greatly impact the urban resilience that is present in the system through the identification of mixed land uses (i.e., residential, commercial, industrial, etc.), amount of green space present in the environment, diversity of structure sizes, the density of the population, and the compactness of the infrastructure that may or may not lend itself to easy connectivity for future alternative water supply structures [9,25]. Redefining portfolios, examining existing policies, and proposing new policies or amendments to old policies were a part of the structure of this metrics assessment.

3.2. Scenario Design

A drought scenario was created using the Water Evaluation and Planning tool (WEAP) [26] in order to see how the Regional Water System would perform under extreme drought conditions. WEAP is a computer modeling tool that uses an integrated approach to model water systems and policy, with attention to both supply and demand side management.

The drought scenario projects what may occur if San Francisco experienced another extreme drought period akin to the 5-year drought that occurred from the year 2012 to 2016. In this scenario, the climate change projections, specifically the predictions for precipitation for the years 2018–2060, were used to help identify which years in the future are likely drought years. Historical precipitation records were used to understand what amount of precipitation is depicted in a very dry, dry, normal, wet, or very wet year. Historical information on previous major drought periods combined with climate change predictions and historical precipitation were collectively used to create and characterize very dry, dry, normal, wet, and very wet years.

The individual alternative water supply options and combined portfolio options results were assessed under this scenario. Special attention was also paid to the way the extended drought affects reservoir levels, unmet demand, supply requirements, and current water system consistency. The expectation was that reservoir inflows would be severely lower than the inflows that occurred during the previous 5-year drought. Reservoir water levels were also predicted to decrease due to considerable variation in precipitation events during this scenario and increased annual temperatures. We expected that the portfolios containing the desalination options would have the lowest unmet demand and the highest reliability due to the process of desalination not being dependent on rainfall or a finite reservoir resource. We considered that the conservation techniques would play a major role in preserving and offsetting the pressure on the water supply options, as it did for the previous 5-year drought, since it is focused more on demand-side management.

In conclusion, the development and validation of the drought resilience matrix were undertaken with a comprehensive approach, aiming to integrate both ecological and socioeconomic factors critical for assessing drought resilience in urban water systems. The matrix's construction was guided by the recognition of the multifaceted nature of drought resilience, incorporating inputs from a wide range of stakeholders, including water resource managers, urban planners, and community representatives, to ensure its relevance and applicability. Validation of the matrix involved its application to the San Francisco urban water system, leveraging the WEAP system for scenario analysis. This process highlighted the matrix's capability to evaluate water supply alternatives effectively, though it also underscored the need for further refinement to integrate social aspects more fully at the residential level. Specifically, the matrix's current iteration could benefit from incorporating considerations of equity and the differential impacts of water supply alternatives on various demographics within urban populations. Such enhancements would improve the matrix's utility in not only assessing but also guiding the development of more resilient urban water systems in the face of drought and other stressors. This iterative development and validation process underscores our commitment to evolving the matrix into a tool that holistically addresses the complexities of urban water system resilience.

4. Results and Discussion

SFPUC is seeking to improve the reliability of the Regional Water System in the face of climate change and drought through the incorporation of new water supply alternatives. These water supply projects vary from the creation of wastewater recycling facilities to Tuolumne River diversions and collaborative desalination plants. Increasing water storage in the form of reservoir expansions is also being considered by SFPUC. Three potential portfolios composed of a combination of different alternative water projects for San Francisco are created here. The portfolios were selected to represent a broad spectrum of solutions, from traditional to innovative, to address the multifaceted nature of drought resilience. Portfolio A contains the Tuolumne River diversions, conservation technique projects, and Los Vaqueros reservoir expansion. The projects in Portfolio A focus on combining small-scale water supply projects that would be added to the existing infrastructure or current practices, making the cost of each project more affordable. Portfolio B comprises the Bay Area Regional Desalination Plant, the East-Side and West-Side Recycled Water Projects, and the Daly City Project. Portfolio B placed more emphasis on the use of recycled treatment plants as an additional water source. These recycled water treatment plants would be located in the city of San Francisco and would use wastewater from the Oceanside or Southeast Wastewater Treatment Plants as influent that would be treated and used for nonpotable uses. This portfolio also attempted to increase SFPUC's communication and collaboration with other water agencies and districts to foster a sharing of information and innovative ideas through the desalination project. The Bay Area Regional Desalination Plant is a project that requires a lot of collaboration, and this could add resiliency to the Regional Water System by having institutions share a resource and potentially build water resources together, coming up with more holistic and innovative solutions. Moreover, finally, Portfolio C contained the local but large water-yielding East-Side Recycled Water Project, the In-City Desalination, and the conservation techniques. This portfolio was arranged with the intention of placing more focus on local solutions' SFPUC, fortifying their water supply through droughts.

In this study, we acknowledge the importance of considering the environmental and social ramifications of water supply portfolios, with a particular focus on their impacts on local ecosystems and vulnerable communities. While our analysis provides a foundation for understanding the broader implications of these portfolios, detailed, portfolio-specific assessments remain essential for fully grasping their ecological and social impacts. Future research should aim to explore these aspects in depth, ensuring that water management strategies are both environmentally sustainable and socially equitable.

Portfolio A received a drought resilience score of 49 out of 55 points. When the individual water supply alternatives were assessed using the four metrics, Portfolio A lost points from the Tuolumne River Diversion Project because the 18 MGD allowance would be limited during drought years, and while that helps to prevent further harm to the natural environment, it limits the amount of water available for SFPUC during those drought years. It makes the Tuolumne River Project less attractive for use concerning drought resilience because the yield does not significantly increase the functioning of the Regional Water System during drought. The same project also cost Portfolio A points because these diversions would be added to the diversion that is already being taken from Tuolumne River to be used by Hetch Hetchy Reservoir to satisfy the needs of SFPUC. This project has the potential to create a negative feedback loop during a drought where water in the Tuolumne River is lowered, leading to less water available in Hetch Hetchy Reservoir, and any additional water diverted downstream would negatively impact the downstream communities and doubly decrease the amount of water supply available for the competing uses. It could also lead to the exceedance of the minimum environmental flow requirements that SFPUC must uphold for instream flow in the Tuolumne River.

Portfolio B received a drought resilience score of 38 out of 55 points. Portfolio B lost points when the four metrics analyzed each water supply alternative due to issues associated with the Bay Area Regional Desalination Plant. This desalination plant requires much collaboration as it is a project in which SFPUC is partnering with six other water districts. While this desalination plant would provide 9 MGD and 10–25 MGD during both nondrought and drought years, it comes with a series of complications regarding the conveyance of the water from the Mallard Slough Plant to SFPUC customers. Multiple entities competing for the same limited capacity make the use of this water supply source more complex during drought years. There are also environmental considerations for this project, where the brine from the desalination plant could impact the surrounding water bodies' water quality, affecting sensitive fish communities [22]. Some institutional considerations and constraints caused this portfolio to lose points as well. The desalination plant would require complicated negotiations between SFPUC and all six water districts and participating permitting agencies. This could cause the timing of the project from construction to implementation to be longer, costing SFPUC more and increasing their financial sensitivity to climate change as they wait for the project to come online. Only one point was lost, from the potential that the public's perception of desalination may be harmful, and acceptance of consuming desalinated water would be hard to encourage.

Portfolio C received a drought resilience score of 52 out of 55. This portfolio lost points when its alternative water supply projects were assessed under the four metrics because of the desalination process and a part of the East-Side Recycled Water Project. The desalination in this portfolio is the In-City Desalination Plant, and it offers 25 MGD, with its source being the Pacific Ocean, making it a very drought-resilient source. However, there could be challenges acquiring the necessary permits because of the various review cycles and feasibility studies that would have to be conducted. There are also limitations on where this desalination plant could be located because of densely populated areas near the coast. To some, the desalination plant may also not be aesthetically pleasing, and just like with the Bay Area Regional Desalination Plant, the public may push back because of negative perceptions of the treatment and taste of desalinated water. The East-Side Recycling Project offers up to 2 MGD for nonpotable uses. The only two drawbacks of this project are that it is one of the lower-yielding projects, and customers that would be served by it (for landscape and irrigation) may have to undergo retrofitting to allow the conveyance of the water, and this would interrupt the current operations of the facility, which prolongs the use of the water and can be very expensive. However, overall, the ability of this portfolio to aid drought resilience based on its score was the highest out of the three portfolios.

In our study, we explored the potential scalability and transferability of the drought resilience matrix, in conjunction with the WEAP system, to urban areas beyond San Francisco. Recognizing the universal challenge of drought and population increases, our framework offers a versatile tool for urban water management across diverse geographical regions. The combination of WEAP's flexible structure and the comprehensive evaluation facilitated by the drought resilience matrix allows for a holistic assessment of water supply alternatives, incorporating ecological, economic, and policy considerations. Although WEAP's modeling capabilities are extensive, including the ability to differentiate priorities among municipal, environmental, and agricultural water demands, we identified a gap in its capacity to fully integrate social and political factors, such as the impact of climate change on different communities and the public's perception of water supply solutions like desalination. The drought resilience matrix addresses these aspects, making it an indispensable tool for evaluating water supply alternatives against the backdrop of social and political considerations. This integrated approach not only enhances stakeholder engagement but also encourages a more nuanced understanding of the potential impacts and acceptance of proposed water management strategies. By highlighting this framework's adaptability and the need for further testing in various urban contexts, we advocate for its standardization and reproducibility in addressing the pressing challenges of drought resilience and sustainable urban water management globally.

In recognizing the critical role of public perception in the success of water supply alternatives, particularly desalination, our study expands the drought resilience matrix to include community acceptance as a key factor. Public perception is increasingly acknowledged as a determinant of project feasibility and sustainability, prompting us to integrate methods for gauging and incorporating this aspect into our evaluation framework. This involves leveraging survey data and community feedback mechanisms to capture the diverse views and concerns of residents. By doing so, we ensure that the matrix not only assesses the technical and environmental viability of water supply projects but also reflects the level of community support and potential for successful implementation. This approach underscores the importance of aligning water management strategies with public values and expectations, thereby enhancing the overall resilience of urban water systems to drought.

This study's exploration of drought resilience through the assessment of various water supply portfolios offers pivotal insights for urban water management policies. Locally, our findings serve as a strategic guide for cities like San Francisco, suggesting the importance of selecting water supply options that not only meet immediate urban demands but also enhance long-term drought resilience. This approach encourages local authorities to consider a blend of traditional and innovative water management strategies that can adapt to changing climate conditions and population growth. Nationally, the research underscores the necessity for policies that support the integration of such diverse strategies into a cohesive framework, promoting sustainability and resilience across urban water systems. By highlighting the effectiveness of different portfolios in addressing drought resilience, we advocate for policy reforms that prioritize flexible, integrated water resource management. This is crucial for preparing urban areas to effectively navigate the complexities of future water-related challenges, ensuring both the sustainability of water resources and the resilience of communities against drought.

5. Conclusions

The use of the drought resilience matrix allowed for the successful assessment of water supply alternatives that may be employed in San Francisco, California. Portfolio C was found to have the highest drought resilience score (52), with Portfolio A coming in second, with 49 points, and Portfolio B coming in last, at 38 points. This is a result of interest because Portfolio A is the best portfolio for SFPUC based on the cost analyses. Yet, here, regarding drought resilience, Portfolio C provides the most benefits. It would be worth re-exploring those portfolios to see if the high population growth was a part of the cause for the difference in portfolio choice. It appears that the more expensive portfolios and water supply alternatives with greater yields produce higher drought resilience. Portfolios C and A are both drought-resilient, but the goals of the water managers and what is most important may determine which portfolio is chosen. If drought resilience and low cost are the most important factors, then a different portfolio would be suggested, but if yield and drought resilience are the most critical factors, the suggestion may change. Portfolio C displayed high marks for most of the metrics due to its type, cost, yield, reliability, institutional, construction, implementation, and public perception considerations.

This matrix could be adapted to be used in different urban areas. It has successfully been applied to a complex urban water system that suffers from drought with results that will have implications for managers' and planners' choices of water supply alternatives to implement. We desire for this matrix to be used in areas across the United States that also struggle with drought and have created opportunities to increase their water systems' resilience.

The limitations of the drought resilience matrix stem from the lack of inclusion of certain social aspects on the residential level that should be considered when planning for drought resilience. Understanding the effect of the implementation of specific water supply alternatives on different demographics of San Francisco residents would have allowed the matrix the ability to identify potential equity issues with how different communities would be affected. Political underpinnings of resilience could only be incorporated into the framework in a more general way in terms of looking at the collaboration between state and local water authorities. The drought resilience matrix could be made better with the incorporation of strategies that help to assess the equity of the proposed water supply alternatives. The drought resilience matrix may have some limitations concerning the scale it can be used on and its ability to factor in those potential unintended consequences. Studies have shown that resilience sought on a community-level scale could have adverse effects on the resilience of households [6,27,28]. To alter the drought resilience matrix, the addition of a way to look at communities and households that are most impacted by drought in the area of study, cross-referenced with the access to the water distribution system and associated poverty issues, would need to be molded into a quantifiable metric to aid the matrix in its ability to capture the effects of drought resilience decisions holistically. More work can be carried out to bolster the matrix and allow it to be used in other urban areas by engineers, managers, and planners.

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