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A Qualitative Definition of Reliable Water Supply for Public Water Systems

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Key Points:

- We propose a universal definition for reliable water supply based on literature and interviews with water managers.
- Reliable water supply is comprised of three overlapping components: hydrology, infrastructure, and governance.
- This qualitative definition forms the basis for future quantitative evaluations and policy measures for water accountability.

Abstract

"Reliable water supply" does not have a clear definition in the Western United States, where water resources are limited and such a definition would be especially useful. In Utah, the three water agencies and 500 public water systems have no consistent method to define, evaluate, and report it, potentially leading to an inability to meet regulatory water demands. We propose a unified definition of reliable water supply for Utah's public water suppliers that can also be used elsewhere. The qualitative definition we propose is necessary to precede quantitative evaluations, set policy, and provide consistency to water resources management. We derive our definition from a two-part qualitative analysis: 1) an extensive review of existing definitions in industry and academia and 2) semi-structured interviews with managers of six diverse Utah water utilities. We propose that water supply be defined by three overlapping components—hydrology, infrastructure, and governance—and that reliability be defined by the capacity of the limiting component.

1 Introduction

Water systems throughout the Western United States and other water-scarce regions devote substantial effort to water supply planning to meet water demands in their service areas. This often includes estimating existing and future demands and developing the necessary water sources to meet those demands. Utah is engaging in extensive efforts to adequately plan for anticipated future water demands by 2060, as seen in recent legislative efforts (OLAG, 2015) and statewide studies that elaborated on these issues (HAL & BC&A, 2019; DWRe, 2021).

A weakness in Utah water planning is the abstract concept of "reliable supply" for public water suppliers. Accountability for this important facet of water management is encouraged by state officials but not required, and the state's three water agencies (Division of Water Resources, Division of Water Rights, and Division of Drinking Water) and 500 public water systems have no consistent method to define, evaluate, and report reliable water supply. This concept is important as it is the foundation to water resources planning that should be considered separately from demands. While efforts over the past 10 years have improved accountability for water demand through water conservation plans, drinking water design, and statutory water use reporting, water supply has no equivalent expectations (Hopkins and Sowby, "Policy Alternatives for Water Supply Accountability in Utah," manuscript under review, *Utilities Policy*).For a water supply policy, it would be essential to establish a qualitative definition for a reliable water supply that sets a consistent metric.

The Utah State Water Plan, published by the Utah Division of Water Resources (DWRe), states that "reliable water sources are vital to Utah's future" (DWRe, 2021). Current estimates of reliable water supply completed in Utah are limited in their analysis, with the option of in-depth analysis being left to individual water systems. This can be insufficient as the abstract concept of supply can be defined differently, and there are larger parameters that go beyond jurisdictional boundaries of a single system. The report states that water supply is confined by three parameters: mechanical constraints, hydrologic constraints, and legal constraints. The existing assessment tool used by DWRe takes the lesser of either the available ground- or surface water supply and compares it to the respective water right limit, contract limitations, treatment capacity, safe yield, and pump capacity to determine a supply. With future water conditions expected to worsen based on the growing population, aging infrastructure, and climate change, a consistent definition of a reliable water supply is becoming more critical.

The reliability of water supplies in planning practice has often been overlooked. Changing climate, regulation, population growth, and uncertainty have impacted the way that these water systems have evaluated existing and future water supplies (Ahmad, 2016). Studies have shown that a reliable water supply can directly impact economies, public health, and the environment (Delta Independent Science Board, 2021). Guaranteeing a future water supply, given the current status of water resources in the Western U.S. (Wheeler et al., 2022; Abbott et al., 2023), is becoming an increasing concern. Research points to the need for a universally understood definition of, and readily applicable metrics for, reliable water supply that considers multiple constraints. Furthermore, this notion must be adaptable so it can be used by each system in Utah and possibly other areas with similar water resource issues.

Despite the importance of a reliable water supply, there is no consistent definition of the hydrologic, infrastructural, or governance components, or guidance on how to evaluate them. We aim to fill this need. While we use Utah as the basis for our research, other states and water managers face the same challenges and we expect our results to be widely applicable, though local details may change. DWRe has prioritized defining water supply reliability and developing reporting guidance and is our partner in this work.

We develop a working definition of reliable water supply and examine the literature, conduct interviews, and document our findings to support the definition. Our definition provides the qualitative basis for water managers to evaluate reliable supply, regulators to provide guidance on management, and policy leaders to design policies for water supply accountability.

2 Proposed Definition

The definition we propose considers three constraints crucial for a reliable water supply: hydrology, infrastructure, and governance. The overlapping consideration of these three components when evaluating a source establishes this as a valuable definition for reliable water supply, which is conceptually illustrated in Figure 1.

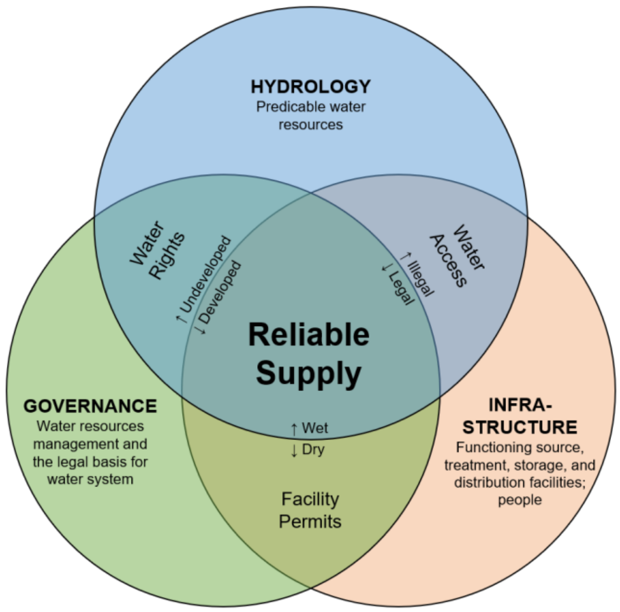

Figure 1.
Reliable water supply components

Hydrology includes measurable water resources and the identification of a raw water supply. It is the most visible component of reliable water supply in our definition. This is what many might call “wet” water. A supply in our definition without actual hydrologic sources would be “dry.”

Infrastructure is the systems necessary to deliver water to end users. It includes treatment, storage, distribution, and people (operators). There are many working components in a water system that need careful planning for effective water delivery; infrastructure addresses the physical capacity of those facilities. Where infrastructure and hydrology share common ground in our definition there is water access: the proper architecture to provide water to end users. A supply without infrastructure would be undeveloped.

Governance, the final component, considers the legal basis of a water supply. It includes the management of the water system in guaranteeing that it meets regulatory requirements. It also considers decisions that water managers make in supply planning. It overlaps with the other components through the administration of water rights or “paper water” (for hydrology) and facility/operating permits (for infrastructure). A supply without governance would be illegal (e.g., water theft).

All three components are necessary for a reliable water supply. It must be wet, developed, and legal. A water system may have an aquifer, but no water rights; a water treatment plant, but no flow; a pump station, but no operating permit. Missing any one of them will not provide water, and a limitation in any one of them will limit the reliability of the supply. The novelty of the definition is the ability to condense the components into one figure making it readily applicable to any analysis.

3 Methods

The proposed definition is supported through a qualitative analysis comprised of two components: an extensive review of existing definitions in academic and industry literature, and semi-structured interviews with water utilities in the state of Utah. We examine the literature on reliable water supply for relevant definitions, methods of measurement/analysis, various factors considered, and important concepts discussed. The information gathered from the evaluation of existing definitions is used to prepare an interview protocol. We proceeded to carry out six semi-structured interviews with water managers throughout Utah and analyzed their responses for consistency with the preliminary definition. This analysis also considered any substantive changes based on the responses.

3.1 Existing Definitions of Reliable Water Supply

We sought the literature on reliable water supply to find existing definitions. Papers were focused on water supply and attempted to explain the numerous factors associated with it. The list of papers we compiled included reports and studies completed by water utilities in the Western United States. We desired to focus on areas that were experiencing similar water planning issues as Utah. For this reason, the criteria of inclusion in the analysis was focused on regions with a similar climate, water sources, and development type to Utah.

A total of 66 papers were reviewed; 19 met the inclusion criteria and provided a reasonable analysis of reliable water supply. We used the same method for each of the 19 documents to summarize the various concepts discussed. We first acquired information from the studies and cataloged what they deemed to be relevant factors of a reliable water supply. This was done by identifying any explicit definitions of a reliable water supply and what components of the water system were considered in that metric. The definitions in the papers were further compared to our definition for solidification of the three components we propose to use in defining a reliable water supply.

Given the variety of definitions and explicit interpretations, the methods of the paper were evaluated with a textual analysis to identify important factors of a reliable water supply. This analysis was then simplified into the categorization of important concepts considered in a reliable water supply. Results were summarized and discussed for each paper. The analysis attempted to address a reliable water supply and look at supplementary information and how it fits within the categories of our definition.

The adequacy of our definition will be tested by observing how key variables identified in the literature fit within the definition. We also identify further gaps in the literature and how our definition considers the extensive number of variables that impact the reliability of a water supply.

3.2 Interviews (Industry Outreach)

To understand how our definition in Figure 1 compares to existing practices, we conducted industry outreach on six water systems in Utah. The basis of this analysis is qualitative, aimed at understanding how the definition would apply in real-world scenarios and how these interviews can support the basis of our definition. To be truly effective, the definition should apply to a wide array of water systems.

We drafted a protocol for the interviews to provide a guideline for the discussion. It was a semi-structured interview aimed at gathering an understanding of how water managers perceive reliable water supply. Semi-structured interviews have pre-determined questions for consistency across all interviewees, but the responses are open-ended in order to allow the participants to describe what is important to them. (Longhurst, 2003; Galletta, 2013).

We asked a total of 20 questions to probe what components of a water system would be considered in reliable water supply planning. We asked questions about explicit definitions of reliable water supply and what the interviewee deems to be the main components or constraints. Further questions were centered around planning practices for their supply considering our working definition of hydrology, infrastructure, and governance. Examples of interview questions are the following, with the full set of questions being provided as supplemental data:

1. “What things do you think would impact your supply?”
2. “What challenges does hydrology planning currently face?”
3. “What challenges does regulation have on your planning capacity?”
4. “What various sources do you consider in your supply?”
5. “What are some water supply planning activities that you participate in now?”

We selected interviewees in an effort to reflect the diversity of size, infrastructure, regions, and operating conditions of water systems in Utah. Table 1 summarizes some pertinent system characteristics.

Table 1.

Water system summary

Water system	Organization	Service type	Service population	Water sources	Setting
Water System #1	Municipal	Retail	83,000	60% ground, 40% import	Urban
Water System #2	Municipal	Retail	115,000	85% ground, 15% import	Urban
Water System #3	Municipal	Retail	3,750	100% surface	Rural
Water System #4	Water District	Wholesale/Retail	800,000	65% surface, 15% ground, 20% import	Urban
Water System #5	Water District	Wholesale	1,500,000	Surface, ground	Urban, Rural
Water System #6	Water District	Wholesale	700,000	Surface, ground	Urban

Interviews were one hour long over Zoom and the conversations were automatically recorded and transcribed. Anonymity was provided to the interviewees and an exemption from our Institutional Review Board was received for this activity. The transcripts from the interviews were analyzed for key terms that were considered in a reliable water supply. This was completed iteratively to differentiate key elements within each of our components of a reliable water supply.

4 Results and Discussion

4.1 Reliable Water Supply as Discussed in the Literature

The analysis of the literature is summarized in the Appendix. Each paper was assigned an ID and ordered chronologically. The information in the “Method” and “Definition” columns show that actual measurements of reliable water supply in the papers are more varying than the definitions used given that they are all unique. More on each of these results will be discussed in subsequent sections. Although there were common themes that appeared in the literature, it was overwhelmingly evident that there is minimal understanding of water supply reliability industry-wide (Delta Independent Science Board, 2021).

Furthermore, it shows the potential impact of our definition in providing a standard that can be used in water resources, whether it be a precursor to a more rigorous quantitative analysis or the initial stages of policy focused on water supply reporting.

There are several water districts in the Western United States that have carried out water reliability studies which support the development of long-term water supply plans. Five of these are large water districts, serving millions of people, that oversee the operations of hundreds of water systems, similar to Utah and the DWRe. These researched areas include the Municipal Water District of Orange County (MWDOC) (CDM Smith, Inc., 2018), Sacramento-San Joaquin Delta (Delta Independent Science Board, 2021), Santa Fe (Rehring, 2011), Bay Area Water

Supply & Conservation Agency (BAWSCA) (CDM Smith, Inc, 2015), and Los Alamos (Daniel B. Stephens & Associates, Inc., 2018).

4.1.1 Definitions of Reliable Water Supply

Of the 19 analyzed papers that met the decision criteria for studies evaluating similar issues to water supply in Utah, eight of them provided an explicit definition. We consistently found that the definition provided, if any, did not encompass the entirety of what was applied in their analysis. The challenge arose from the difficulty of condensing all the identified variables from their analysis into a comprehensive definition. Often, the approach involved simplifying a definition to a single measurable output, such as meeting water demands.

Of the eight provided definitions, many of them focused on the ability and/or probability of successful water delivery. This was expressed in terms of either the performance of a particular system component or the failure frequency. Although these definitions are useful for understanding the infrastructure component of a water system, they do not consider other important factors, such as governance and the physical water supply (hydrology).

The five studies by water districts on the reliability of a particular water system's supply provided the most insight into an existing definition. These studies tried to capture the broad issues surrounding water resources management, and further, the variables that impact that reliability. This included the consideration of economic, social, and political issues that water mangers face.

Of the eight explicit definitions, four explicitly referred to reliability in terms of meeting water demands. Their studies follow the assumption that meeting water demands is the priority within most managers' planning practices and that matching the supply to the demand has been the standard. However, this "demand first" planning assumption is breaking down as supplies can no longer keep up with growth. The Delta Independent Science Board (2021) provided the following definition that turns this assumption around: "matching the state's demands for reasonable and beneficial use of water to the available supply." This is an important insight as current planning practices do not provide a sustainable solution to growing demands and the constant need to obtain more of a finite source of water.

While the definitions both agree and differ on some details, 68% of the literature has been focused on the probability of successful water delivery. This was often expressed in terms of failure based on a predetermined parameter, emphasizing the infrastructure component of a water system. Furthermore, all of the definitions agree on both the hydrologic and governance components; the hydrologic component is incorporated into several of the definitions by considering the variability in a water supply. The physical water supply can be incorporated into the probability of successful delivery and eliminating failures. Effective governance of a water supply is considered in each of these definitions based on the underlying idea that it is necessary to manage the inputs and outputs of the system. Within the papers, 63% of frameworks considered the inputs of water managers and how they may impact the reliability of a supply. Similar ideas can also be seen in one definition by CDM Smith Inc. (2015): "a measure of the quality and quantity of services proved to meet a community's needs and expectations." Our definition captures this notion and helps ensure that the dynamics of a community are considered when developing a reliable water supply. These similarities become even more apparent when analyzing the methods that each of these papers considers.

4.1.2 Methods for Evaluating Reliable Water Supply

Methods used throughout the literature show a variety of techniques used to measure a reliable water supply. Much of the research was computationally complex, utilizing mathematical or statistical models to develop relationships between variables in their analysis.

Water utilities aiming to develop a measurement of their reliable supply consistently used water resource models through linear programming that consider several constraints on their specific water supply. There was a diverse array of variables that impact the supply based on the status of climate, politics, and economy in that area. The five systems that developed water resource models further emphasize the difficulty of applying the same model on a different water system due to the fundamental differences. It would require a new model to be developed for each water system. This idea was shared among several of the studies, regardless of methods used, and points to the need for a definition that is adaptable.

The other 14 studies narrowed down the analysis to a certain component of a water system through several statistical models and frameworks. These ranged from the likelihood that there would be water delivery based on network configuration to the likelihood that customers would pay higher prices for more reliable water.

Our qualitative definition encompasses the objectives of all the methods used to quantify a reliable water supply. To further demonstrate this, we focus on the main factors considered by each of the papers' analysis.

4.1.3 Factors Considered in Evaluating Reliable Water Supply

Each paper considered many factors. We take the main factors and categorize them by the component of our definition they best match, with the percentage of total papers that consider that factor. This analysis is shown in Table 2.

Table 2.

Summary of factors considered categorized by component

Component	**Factors *(% of papers)***	
Hydrology	- Climate change *(42%)* - Water availability *(11%)* - Drought *(16%)* - Environment *(11%)*	- Limited resources *(5%)* - Aquifer depletion *(5%)* - Contamination *(5%)* - Change in precipitation *(5%)* - Weather *(11%)*
Infrastructure	- Looped distribution *(5%)* - Technology performance *(11%)* - Treatment *(5%)* - Leakage loss *(5%)*	- Delivery mechanisms *(11%)* - System capacity *(11%)* - Pipe failures *(5%)*
Governance	- Customer input *(5%)* - Social conditions *(16%)* - Institutional conditions *(11%)* - Water rights *(11%)* - Political conditions (5%) - Policy decisions *(5%)* - Operational management *(5%)*	- Demands *(32%)* - Conservation *(5%)* - Water use restrictions *(5%)* - Growth rates/population projections (26%)
Multiple	- Water quality *(26%)* - Cost/economy *(42%)*	

The textual analysis shown in Table 2 yielded positive results for our definition, as most of the factors considered consistently fit within hydrology, infrastructure, or governance. Some of these factors often overlapped multiple areas and is shown in the “multiple” category. This analysis also shows a significant portion of the papers identified multiple factors that fell within at least two areas of our definition. Breaking the analysis down by recurring factors helps show more specific elements within the larger components. A reliable water supply should, at some point, consider these factors of the three components, as any of them could potentially be a limiting factor.

Figure 2 shows a summary of water supply components that are emphasized in each of the articles. Though the language differs, the main factors of water supply reliability were centered around hydrology, infrastructure, and governance. The results in Figure 2 also show that it is difficult to develop a framework to define or measure reliable water supply without considering a combination, if not all, of the components outlined in our definition.

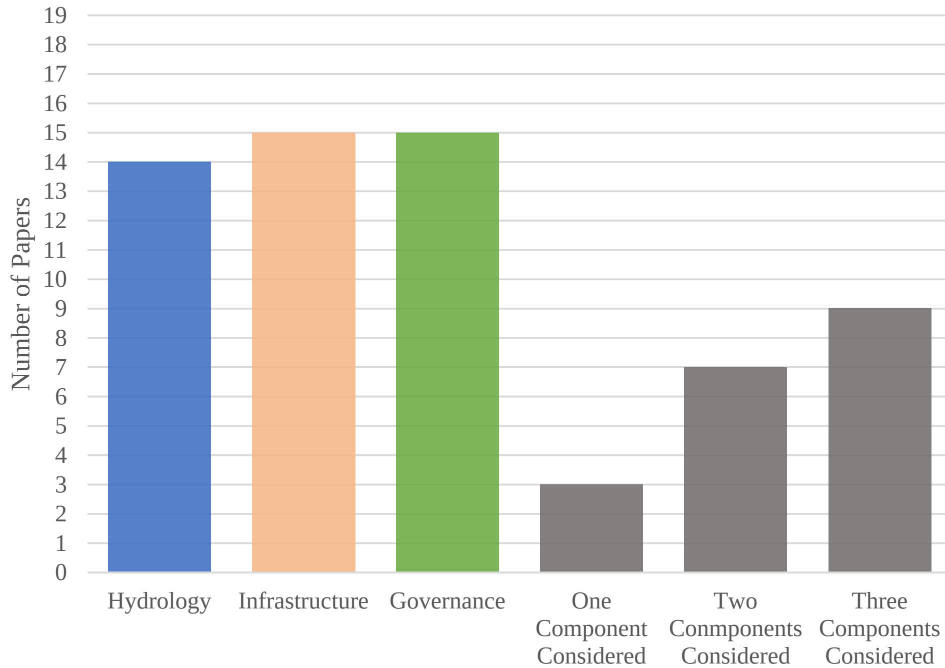

Figure 2.

Summary of methods by reliable water supply component

Hydrologic analysis of reliable water supply in the literature considered climate change, limited resources, and variability in water supply. Climate change is a growing concern for water supply planning and determining a reliable water supply: climate change was considered in 42% of the papers, being the most discussed factor out of the ones shown in Table 2.

Without the proper infrastructure to treat or convey water supplies, there is no guarantee of reliable supply. Here, the literature focused more on the impacts of interconnections between water systems, developing projects that can increase supply, and considering the balance between costs and water provided. Both the technology performance and costs of infrastructure were considered by 42% of the papers in those analyses because it is often the most useful for planning decisions.

For governance the literature centered around water rights, government, and environmental regulation. This is where each paper varied most; they considered both the impacts of existing conditions and how water supply planning decisions could further impact those conditions. Growth rates and economy were the most discussed in this group, with 26% and 21% of the papers considering them, respectively. The economy was often considered more if we include the papers that discussed the costs of infrastructure.

Another frequently deliberated factor was projected water demands, considered by 32% of the papers. Often these analyses stemmed from the need to meet growing demands in a specific water system. Meeting demands was the most frequent measurement of reliable water supply in the definitions. It showed the current procedures used in planning and the stress that it has on water managers. The main focus was to develop a supply portfolio that has room to grow to meet anticipated demands. If anything, the growing constraints shown in our definition should push for water demands to be planned around available supply, not the other way around, as has been the historical practice. Changing the existing narrative on water supply planning to match demands to the available supply helps ensure a sustainable approach to water resources management. Water conservation is a growing practice in Utah (DWRe, 2022), and demand management policies should be a focus of future planning practice. This is necessary given that the constraints around the development of reliable water supplies are clear and large in magnitude. Our proposed definition would help water managers identify the constraints to their water supply. Better knowledge of this finite volume would encourage implementation of water conservation policies.

Overall, this analysis begins to show the difficulties that water managers may face with the number of variables to consider in a reliable water supply. It stresses the reality that decisions they make for their current water supply could impact the future reliability of that supply.

4.1.4 Important Concepts of Reliable Water Supply

Based on the literature review we provide several key conclusions about both water resources planning and reliable water supply. These will shape our working definition and provide a foundation to future research:

- A widely adopted definition for a reliable water supply is missing in practice.
- Variability among water systems makes it hard to develop a universal definition.
- Decisions made by water resource managers are important to reliable water supply.

Our definition encapsulates these conclusions. It fills a gap in water supply planning. The interview analysis presented in the next section will illuminate how our definition accounts for variability among water systems. Our consideration of governance as one of the components in reliable water supply helps consider those decisions made by water resource managers in planning. An overlapping conclusion is that a definition cannot be so advanced that it prohibits use. Our future research will consider this when developing a method to evaluate a reliable water supply.

4.2 Reliable Water Supply as Discussed in Interviews

The interviews yielded similar results to the literature and provided more context to the issues that Utah water systems face. Understanding the process provided insight into a more realistic definition. Answers from utilities varied; responses centered on issues each one is currently facing, whether they be in hydrology, infrastructure, or governance.

4.2.1 Interviewees' Definitions

The first question asked in the interviews was how the interviewees would define a reliable water supply. Most often, the explanation was more than one sentence, often a paragraph, and considered multiple components of a water system. Several of the interviewees attributed a reliable water supply to "mother nature" and the variability that affects year-to-year planning.

Table 3 provides a summary of the main points in their explicit definitions for reliable water supply and, ultimately, what they had deemed the most important factors of a water supply. The definitions varied but provided insight into the components that are considered in planning at each utility size.

Table 3.

Summary of utility definitions of reliable water supply

Utility	Definition
Water System #1	- What "mother nature" does for us and the kind of snowpack that is provided. - Reliability depends on changing ground water levels.
Water System #2	- Long-term quantities of water that are sufficient to meet the needs of the individuals in the system. - Looking at the environmental needs that rely on the water. - The use of water multiple times. - What "mother nature" provides to the basin and the management of that.
Water System #3	- Water that is available 24/7, 365 days a year. - Something that you can count on.
Water System #4	- High degree of confidence that the water can be deployed to make deliveries.
Water System #5	- Water supply that is available to meet current and future demands, with conservation or the development of future supplies
Water System #6	- A supply that has been developed with a certain analysis centered around the desired level of service. - Identifying the uncertainty or risk associated with the water supply and balancing that with water being contracted out.

Water Systems #1, #2, and #3 (municipal water systems) appear to consider a reliable water supply as supply that is provided on a *consistent basis*. They focus on a smaller scale and ensuring that customers are provided with constant water services. Control of water demand is limited as there is continuous growth and changing land uses. Therefore, planning is driven by ensuring that demands are always met.

Water Systems #3, #4, and #5 (water districts) appear to consider a reliable water supply on a larger scale compared to the municipal systems and the *probability* that it can be provided. This was derived from their responses to the interview questions and the recent studies they have completed to predict water supply. They have more resources to complete these planning studies compared to the municipal systems. Smaller water systems encounter greater challenges in water resources planning due to their smaller customer base, as well as a lack of personnel and financial resources (Haider et al, 2013; McFarlane & Harris, 2018).

Water contracts for the districts are based on what they expect to be the available supply. They are not expected to meet a certain demand; they tell their customer agencies the amount of water that can be anticipated and do not guarantee to satisfy the customer agencies' water demands. These concepts are similar to what we found for existing definitions in literature. Many variables have been found to impact a water supply, and a probabilistic approach to measure reliability may help with management.

To understand the finer details of what the interviewed utilities consider a reliable supply, Table 4 shows the key factors in responses that they consider to be the components and possible constraints. We later observed that their responses were framed by what issues they are facing.

Table 4.
Summary of components and constraints considered in reliable water supply

Utility	Components	Constraints
Water System #1	- Groundwater levels	- Groundwater levels
Water System #2	- Physical features of the water system - Aquifer management - Terminal lakes - Water treatment	- Drought - Human interference - Changing land uses - Focusing on surface water supply - Public mentality about water usage
Water System #3	- Watershed - Diversions - Pipelines - Storage reservoirs - Spring development - Wells - Water treatment - Distribution infrastructure	- Drought - Wildfires
Water System #4	- Watershed - Climate and the natural system - Storage reservoirs - Treatment - Infrastructure to end user (pump station, piping, and tanks) - Surface water and groundwater supplies	- Climate variability and climate change - System facilities (condition and capacity) - Competing interests of the public - Maintaining the environment while meeting the needs of the community
Water System #5	- Everything from the watershed to the conveyance system - Treatment and delivery systems - Groundwater and surface water - Snow melt - Vegetation - Soil mechanics	- Size limitation in infrastructure - Aging infrastructure - Natural disasters (wildfires) - Growth - Climate change
Water System #6	- Historic hydrology - Planning - Resiliency - Coordination with customers	- Growth - Drought - Climate variability

Responses categorized in Table 4 show the complexity of a reliable water supply and the numerous elements that are currently considered by each utility. They range from physical aspects of a water system, such as watersheds and pipelines, to the human interactions between customers and utilities. There were also answers focused on natural disasters and recent impacts on their water supplies. Regardless of the type of component or constraint in the response, we are able to categorize them within our definition comprised of the components of hydrology, infrastructure, and governance, just as we did for the literature. The responses showed that effective water supply planning in Utah requires a firm understanding of the water system and the variables that could directly and indirectly impact it.

Furthermore, the responses from the municipal water systems appeared to consider more traditional water resources issues that they may deal with in their planning practices, such as the physical infrastructure and available water supply due to drought. This aligns with the thought that their water is supplied on a consistent basis, ensuring that existing and future demands are met based on growth and changes in land use. This is a deviation from water districts, who plan their water supply in terms of the probability of delivery. The contrast was further derived in later interview questions. We will elaborate on this further in the following sections as well as on the similarities with the existing definitions found within literature.

4.2.2 Interviewees' Comments on Hydrology

The utilities were asked about the challenges they face with hydrology in water supply planning. Answers were focused on the variability of surface water supplies and the changing groundwater levels. Of the components in our definition, hydrology is perhaps the most variable. There are many uncertainties in the physical water supply on an annual basis. The interview responses shared this ideology with the literature. The utilities emphasized that they rely heavily on snowpack on a yearly basis due to the fact that it provides surface water supplies to them either directly or indirectly. All of the utilities pointed to Utah's current historic drought and the concept of climate variability impacting their water supply.

Further questions were asked about modeling and analytical tools that are used to identify the variability of their hydrologic sources. Water Systems #1 and #2 did not conduct any type of modeling, whether it be a probabilistic approach or climate modeling. The only municipal water system to do any sort of modeling was Water System #3. They developed a model to help predict the amount of water in a given year to help plan for adaptable tiered water rates (Sowby & South, 2023). The main objective was to stay revenue neutral while promoting water conservation. Another water system pointed out this concept and stated, "it's not good if we're not charging enough for water, and we don't have enough to cover large projects. There's so many single points of failure in a system."

Water Systems #5 and #6 both study water supply variability and prepare climate models; Water System #4 relies on other water systems' variability analyses. It is not within the capabilities of the municipal water systems we interviewed to do complex climate modeling. It also increases in complexity with the size of the utility. One water system stated, "there is also the uncertainty that is associated with the hundreds of climate change models" and that they have to go through the range of scenarios to determine the most likely to occur; overall, it is a mitigation strategy. Water utilities appear to be overwhelmed by the complexity of climate models. It points to the need to make climate scenarios more interpretable by users for more easily identifiable actions to combat climate change.

Furthermore, one utility emphasized the need to track water production trends in comparison to the climate models. This can help establish the likely scenario that was predicted. These studies are completed to use on a consistent basis and act as a tool that can be referred to in the future. This further emphasizes the need to have a proactive approach in water supply planning.

The main difference between the definitions in literature and the interview responses was groundwater supplies. The majority of the utilities mentioned groundwater supplies as an important component in reliable water supply; definitions in literature focused on surface water. Groundwater levels are a growing issue in Utah and have been at the forefront of statewide planning practices, as seen from the interviews as well as state policy. This can be further seen with the recent development of several groundwater management plans and water right adjudications. There is the understanding that groundwater is often more reliable than surface water, but not replenishable. This ideology was shared among the responses in the interviews, showing there is a need to more properly manage groundwater so it can be a drought mitigation tool. Utilities are working on developing groundwater coalitions in Utah, such as the North Utah County Aquifer Council (NUCAC) and Mt. Nebo Water Agency. Our definition addresses a gap in the literature by considering groundwater and the lack of current analysis in this field.

4.2.3 Interviewees' Comments on Infrastructure

Of the three components of our proposed definition for reliable water supply, infrastructure appeared to be the most consistent between the literature and interviews. It is widely understood that infrastructure is necessary to utilize a water supply; therefore, it should be considered when measuring the reliability. One utility summarized this concept well: "new infrastructure needs to be added to meet the growth and demand of the system."

Respondents were asked the type of sources they consider in their water supply and the infrastructure that is commonly used within their system. Again, answers focused on surface water and groundwater infrastructure. Common components of water systems were water treatment plants, pump stations, pressure reducing valves (PRVs), wells, storage tanks and reservoirs, and pipes. Several respondents suggested that the operations of those facilities is what makes them effective, indicating the overlap between infrastructure and governance.

We then asked which variables or factors these utilities see impacting their infrastructure. The main responses were age, cost, material availability, capacity, design, and the growing needs of the system. The majority of the utilities pointed to the longstanding effects of COVID-19 on their most recent construction projects (Sowby & Lunstad, 2021). One comment from the interviews summarizes these issues well: "we have to both grow and renew and replace a lot of aging infrastructure… [the system is] hitting that stage of life where it needs some significant investments." It has put a lot of strain on them to be able to efficiently plan projects given any unforeseen variables, which was a theme shared with the literature. Both the municipal and water district water systems have experienced these issues. Further, all of the water districts pointed to the need to make their infrastructure more resilient to natural disasters. Given the size of and resources available to the water districts, they are able to think more critically about such issues.

Infrastructure is an important component of water supply as it is the mechanism that delivers it to the end users. This concept has been reviewed extensively in literature and much work has been completed on developing methods to measure its reliability. Our definition considers the extensive list of variables that can impact the delivery infrastructure and encourages water systems to think critically about it.

4.2.4 Interviewees' Comments on Governance

Originally in the analysis, governance was categorized as "regulation." It was believed that regulation encapsulated the legal constraints of a reliable water supply. Further research on existing definitions and responses from the interviews suggested that there was more to it than the legal component. Governance encapsulates both water resources management and regulation, as they deal with the administrative aspects of water planning.

Regulation was a concept that most utilities identified in their responses and was considered to have a large impact on their water supplies. These impacts were manifested from legislation and water rights. Although they were not considered a negative aspect, as one utility states, "laws are important because they allow for the organized, well-functioning use of water." While it was widely understood that they are necessary, regulations still had an adverse impact on water supply planning. This attitude was more commonly seen in responses from the municipal water systems. It was understood that new regulations can hinder their water supply by requiring more work to be completed by an overburdened staff or by limiting what kinds of water sources are acceptable. Certain legislative examples were provided based on the utilities' previous experiences, emphasizing that legislative requirements affect each water system differently. The water districts often did not see regulatory requirements to hinder their planning activities. This could be due to their more proactive role in the legislative process and their singular focus on water issues, both which better prepare them to navigate regulatory changes, while the municipal water systems seem to be more reactive.

When asked how predictable the requirements are, responses varied drastically between the municipal water systems and water districts. The municipal water systems believed regulations to be unpredictable and often difficult to interpret. The water districts pointed to their most recent efforts in being part of the policy process. One utility stated that they engage in "advising and giving input as legislation is developed so that it's done understanding the consequences of the legislation and achieves some objective in solving a problem." They have found that future legislation is often not as unpredictable because they are involved at the early stages of policy formulation. It is a more proactive approach to provide more input on the regulations that may impact their reliable water supply.

Water rights were a prevalent response from each of the utilities as there needs to be a legal basis to the water supply. For half of the utilities, by their own assessment, it was often the limiting factor in their supply, where others were constrained by the current hydrologic conditions or infrastructure capacity. This further supports our definition in the sense that there are many limiting components of a water supply; it is necessary to consider all of hydrology, infrastructure, and governance.

Water supply management was a common theme encountered throughout the analysis. There was a consistent rhetoric in the literature that discussed how water resources management is a rapidly developing field. This was consistent with the interview responses. All of the utilities discussed their responsibilities for providing safe, clean, and reliable water to their customers, as one utility stated, to "make sure that it's used to its highest and best possible use."

There needs to be effective governance of water sources in terms of the hydrologic conditions and the infrastructure used to transport it. Some planning practices that were discussed by the utilities include regional water management, water portfolio development, and demand management. One utility explained the importance of having a diverse water supply: "we do have a diverse supply, and that helps with the reliability. If there's some diversity of supplies, some supplies might be more vulnerable to a drought or other natural hazards than certain others." This is a concept that will be considered in our future work on developing a method for evaluation.

5 Conclusions

Our research shows that a definition for reliable water supply needs to be an all-encompassing theory that considers numerous variables. The qualitative definition that we propose is an overlapping consideration of hydrology, infrastructure, and governance. We support our definition with evidence from literature and interviews with water utilities in Utah. It is a robust definition that allows many existing definitions to be retained and for the concept to be presented in a single figure.

The analysis finds extensive similarities between the literature and interviews, showing the variety of factors that can impact a water supply. Each factor identified aligns with hydrology, infrastructure, or governance in our definition. The definition attempts to fill a gap identified in the literature— the absence of a unified definition—while also meeting the planning and policy of needs for DWRe for a statewide application. Furthermore, it accounts for the variability between water systems and the impact of the decisions made by water managers on a water supply.

The significance of our definition for a reliable water supply is not the accuracy of any one particular analysis but the combination of the three components. This paper outlines the importance of a qualitative definition that can act as the foundation for future research that advances water planning to a more sustainable practice. Our future research identify viable policy options for water supply reporting, develop a quantitative method for measuring reliable water supply, and provide a decision matrix for a qualitative assessment of public water supplies. Incorporating these methods into planning ensures that water systems are doing some minimum level of analysis. Our definition can be used by water systems in and beyond Utah to promote more sustainable water planning.

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Open Research

The interview protocol has been uploaded as Supporting Information for review purposes.

Appendix. *Review summary of existing definitions of reliable water supply*

ID	Source	Definition	Method	Factors considered	Important concepts
1	Howe et al. (1994)	None	Uses a contingent valuation survey to measure water supply reliability in three towns in Colorado. Develops the concept of what customers are willing to pay (WTP) for higher levels of reliability and what compensation they would require (willingness-to-accept, WTA) for lower levels of reliability.	Water reliability, quality, cost, impacts of a water shortage, customers input	Risk preference of consumers. Decisions made by water and public officials who don't understand the risk of water shortages. Water users feel entitled to large amounts of water.
2	Wolff (2008)	"The degree to which the system minimizes the level of service failure frequency over its design life when subject to standard loading."	Measures a constant-reliability unit cost that adapts some concepts from a financial portfolio summary. A unit cost is calculated by dividing the average annual total yield of the option by the annual average total cost (the sum of average annual fixed plus variable costs).	Water managers define the level of reliability they would like to achieve.	There is no widely adopted definition for a reliable water supply. Critical year supply is the amount large enough to satisfy critical year demand, which is often higher than the average to allow room for variability.
3	Chung et al. (2009)	None	Uses a Bertsimas and Sim approach to balance the reliability and cost of the system. This approach lets the user modify the conservative estimate through the analysis.	Growth rates, locations, climate change, water resource availability, changing social and institutional conditions	Increasing conservatism increases reliability as well as cost. Uses robustness as a metric that looks at the water system and how it remains feasible under uncertainty.
4	Basta (2010)	None	Evaluates urban water supply reliability through an econometric analysis of water rights prices, and a case study discussion on several factors influencing urban water supply reliability, vulnerability, and resiliency.	Drought, climate change, population growth, water rights prices, beneficial use, prior appropriation, water transfers, increased water use	Development of water markets in areas with limited water supply. Difficult to use similar indicators for each city because there are different

ID	Source	Definition	Method	Factors considered	Important concepts
			Uses Tucson, Las Vegas, and Portland as case studies.		components for each city's water supply.
5	Rehring & Borchert (2011)	None	Santa Fe developed a long-range plan for water supply users. Developed and compared multiple supply portfolios to address a projected gap between supply and demand. Analyzed these varying portfolios using WaterMAPS, a water resource modeling software.	Portfolio analysis: improve reliability and sustainability, protect the environment, manage costs, ensure technical soundness, ensure acceptability, ensure timeliness	Considers government and citizens when modeling and evaluating portfolios.
6	Martínez-Rodríguez et al. (2011)	"Reliability is defined as the probability that a water supply network will satisfy the design demand"	Discusses two quantitative indices for measuring reliability and tolerance in network behavior.	Looped and branched distribution networks. The distinction between connectivity and capacity redundancy.	Reliability cannot be considered a measure of redundancy for water supply networks.
7	WaterReuse Research Foundation (2013)	"A predictable and reasonably stable target yield, without much variability in or uncertainty about how much water will be produced over a given time interval."	Evaluates customer valuation data with water reliability by estimating the economic value of drought-resistant water yield reliability. Emphasizes the portfolio theory approach and the willingness to pay (WTP) approach.	Weather, climate, emergency events, nonlocal political and institutional factors, energy availability, cost, technology performance, water quality, and delivery infrastructure	Benefits different sectors obtain with reliable water supply, local water generation, importation of water, water reclamation
8	CDM Smith, Inc. (2015)	"Generally defined in terms of a LOS goal, which is a	Attempts to quantify the water supply reliability needs of the BAWSCA member agencies through 2040 and identifies the water supply management	Treatment and delivery mechanisms, policy decisions, hydrologic conditions, regulatory	Partnership development, water shortage allocation plan, assessing costs to meet varying levels of

ID	Source	Definition	Method	Factors considered	Important concepts
		measure of the quality and quantity of services provided to meet a community's needs and expectations"	projects and/or programs that could be developed to meet those needs. This is based on a quantitative and qualitative weighted grading process for each project.	actions, system capacity constraints, climate change, economy	reliability, large economic impacts are given for supply shortfalls.
9	Ahmad et al. (2016)	None	Evaluates the impact of climate change on the Colorado River with various global climate models given different scenarios and the potential impact on water supply.	Climate change, demand management policies, growing populations, indoor and outdoor conservation, water pricing	Change in climate decreases water supply reliability.
10	Butler et al. (2016)	"The degree to which the system minimizes the level of service failure frequency over its design life when subject to standard loading."	Develops a framework that uses reliability, resilience, and sustainability and how threats, systems, impacts, and consequences allow for this model to be made applicable in any situation. Relationships are developed between each part of the framework including mitigation, adaptation, coping, and learning.	climate change, urbanization, asset deterioration, limited resources, tightening regulation, and long-term social, environmental, social, and economic consequences	Connectivity, system adaptability, threat identification
11	Gheisi et al. (2016)	"The ability of the system to accomplish its mission during a specific time interval at various operation conditions."	Categorizes reliability into three categories: mechanical, hydraulic, and water quality. It measures risks in terms of pipe failures and pipe failure combinations.	Probability of pipe failure, pipe failure combinations, natural disasters	Reliability based on water quality failure
12	Goharian et	None	Develops a cumulative distribution	Reliability, resiliency,	Making decisions in

ID	Source	Definition	Method	Factors considered	Important concepts
	al. (2017)		function (CDS) and derives an index Water System Performance Index (WSPI) to measure the magnitude and frequency of a failure in a water system. This was tested on two reservoirs for the Salt Lake City Department of Public Utilities.	vulnerability, operational management	multicriteria analysis is difficult as different systems have different preferences.
13	Zeraebruk et al (2017)	"The percentage of time that the water supply system is able to meet the full demand."	Measures a water balance based on modeling the safe yield and corresponding reliability of reservoirs. Models this water balance using SWAT (Soil and Water Assessment Tool). They used the results from the model to assess the existing water supply situation and challenges in the future.	Water demand, effective water governance, management, reducing leakage losses, population growth, economic growth, climate change	Safe yield, which depends on storage and hydrologic characteristics of the source.
14	CDM Smith, Inc. (2018)	None	Study for Municipal Water District of Orange County. Phase 1 evaluated initial supply gap; Phase 2 developed regional water resource portfolios. Uses Water Evaluation and Planning (WEAP) tool for many scenarios.	Climate change, demand projections, water use restrictions, weather factors	Water gap, adaptive management
15	Erfani et al. (2018)	None	Focuses on using a least-cost scheduling approach for water infrastructure investment planning. with Real Options Analysis (RO).	Demand reduction policies, climate change	Capacity expansion problem, robust decision making, deployable output
16	Daniel B. Stephens & Associates, Inc. (2018)	None	A long-range water supply plan for Los Alamos that looked at providing a sustainable water supply for the next 40 years based on available supply, water quality, and water rights.	Aquifer depletion, contamination, water rights administration, senior water rights, water demand, population projections, climate change, drought, and	Active water resource management, water audit software, reconciliation of supply with demand, water conservation

ID	Source	Definition	Method	Factors considered	Important concepts
				change in precipitation	
17	Ren et al (2019)	None	Develops a framework that evaluates the performance of a water supply system considering the encounter between different water sources. Uses a simulated annealing algorithm and fragment method. Performance is measured with reliability, resilience, and vulnerability.	Future water demand, supply growth, decision makers' preferences, system structure, incomplete input information	Weak predictability of input information is one of the biggest challenges when looking for applications of water operation models. Uncertainties increase with more resource inputs.
18	Escriva-Bou et al. (2020)	None	Evaluates each system's water accounting practices and identify important concepts. It looks at institutional and legal frameworks, how water use is quantified, and how water decisions are made based on regulatory and physical constraints.	Water accounting, physical constraints, modeling, water use	Water assets, water liabilities, information sharing, establishing standards, centralized information management systems
19	Delta Independent Science Board (2021)	"Better matching the state's demands for reasonable and beneficial uses of water to the available supply."	Study on the Sacramento-San Joaquin Delta water supply. The Board identifies the importance of reliability, conducts an analysis of water supply reliability, and analyzes management and policy. Builds upon research on other water systems, academic articles, and industry surveys.	Economics, social impacts, public health, drought, natural catastrophes, sub-optimal system management, portfolio management, applicability, water resource modeling.	Unreproducible analysis with no testing, adaptive management, equity of regional water management among diverse entities

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Interview Protocol & Guide

Introduction/Framing

Introduce myself (very brief)
Purpose of interview to understand more about reliable water supply and planning

- not looking for any particular answer
- no axe to grind

Ask how much time he/she has allotted for this interview
Explain anonymity and consent.
Explain OPEN format of interview.
Ask permission to record interview.

Explain that we are going to be using this information for this and other related other projects

Context

1. What is your professional involvement with water resources planning?

2. How would you define reliable water supply?

3. What components of a water system would you consider to be a part of reliable water supply?

4. What are things you would consider a constraint of reliable water supply?

5. What things do you think would impact your supply?

6. What things would you consider when thinking of your reliable supply?

7. How would you factor water demands into your concept of planning?

Hydrology

8. ***Intro Q:*** What challenges does hydrology planning currently face?
   - **Probe** – legislation, and codes (lack of guidance)
   - **Probe** – climate change
   - **Probe** – variability
   - **Probe** – extensive modeling analysis
   - **Probe** – costs (economics)
   - **Probe** – environmental
   - **Probe** – technical

9. ***Critical Follow-up:*** How do you consider this in your planning?
   - **Probe** – examples

10. ***Critical Follow-up:*** What is a better way of analyzing it?
    - **Probe** – examples

Regulation

11. ***Intro Q:*** What challenges does regulation have on your planning capacity?
    - **Probe** – legislation and codes
    - **Probe** – political issues
    - **Probe** – water rights
    - **Probe** – water operating permits
    - **Probe** – technical
    - **Probe** – EXAMPLES

12. ***Critical Follow-up:*** What factors do you consider in water supply related to regulation?
    - **Probe** – limiting factors

13. **Critical Follow-up:** How predictable do you believe regulation requirements are?

Infrastructure

14. **Intro Q:** What various sources do you consider in your supply?
    - **Probe –** measurement

15. ***Critical Follow-up:*** What guidelines do you use for infrastructure capacity?
    - **Probe –** DDW standards and rules

16. ***Critical Follow-up:*** What variables do you see impacting infrastructure?
    - **Probe** – legislation and codes
    - **Probe** – costs (economics)
    - **Probe** – environmental
    - **Probe** – technical

Planning

17. ***Intro Q:*** What are some water supply planning activities that you participate in now?
    - **Probe** – water portfolio development
    - **Probe** – components considered

18. ***Follow up:*** What current analytical tools do you use?

19. ***Follow up:*** How are you accounting for increasing water demands?

20. ***Follow up:*** Do you work with other municipalities?

END QUESTIONS

I greatly appreciate you for taking the time to meet with me today and answer some of these questions.

Final Questions

- Anything else that is important to consider?
- Anyone else that you recommend that we talk to?
- If I have follow up questions, is that okay to talk to you?

Other Data: