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From Mosaic to Systemic Redux: The Conceptual Foundation of Resilience and Its Operational Implications for Water Resource Management †

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Abstract: Preserving and enhancing the resilience of water supply systems is an important goal for managers to help ensure the ongoing availability of a resource necessary to both economic activity and basic survival. If not explicitly identified as a goal, it can be inferred from the desire to preserve water supply against a variety of stressors for current and future generations. Pursuing resilience is less than straightforward as there are multiple concurrent theoretical paradigms. Furthermore, operationalizing even one of these can be challenging. The authors survey several dominant paradigms with an eye towards distilling the essential, combinative properties of resilience. The contention underwriting this approach is that each paradigm yields important insights about resilience as a complex, emergent system characteristic. This survey lays the foundation for the operationalized approach that is the central thrust of the paper. Specifically, the authors develop an equation based on these properties and identify water resource metrics that correspond to each property. The analysis concludes with a preliminary causal loop diagram intended to capture key system variables and relationships between them. The authors argue that a systemic, conceptually robust approach to resilience is necessary to (1) assess current levels, and (2) improve levels of water resource system resilience.

Keywords: resilience; water resource management; resilience properties; social-ecological systems

1. Introduction

Many people in developed countries take it for granted that when they turn the faucet on, they will receive clean drinkable water. This implicit assumption is a testament to those responsible for managing and delivering water resources. Doing so is a complex endeavor characterized by the dynamic balancing of competing goods from multiple stakeholders and considering diminishing certainty about supply availability. There is growing recognition among water resource researchers, managers, advocates, and consumers that current water resource management practices are incapable of meeting not only today's demands but tomorrow's as well. The U.N., for example, estimates that water demand has grown at approximately twice the rate as the population has [1]. Moreover, the World Bank estimates that demand will outstrip supply by 40% a mere 11 years from now [2]. This is not a problem unique to developing countries. The recent crisis in South Africa illustrated that even progressive water systems are more fragile than was anticipated [3]. Developing and developed countries face a looming water crisis. The scope of this challenge, coupled with the complexity inherent in water resource systems, reveals the role that systems thinking can and should play moving forward. That is, the application of both systems theory and tools can be tremendously useful in water resource management (WRM). Loucks and Van Beek define WRM as the management of "three interactive subsystems" that each impact water: The natural, socio-economic, and institutional [4]. The natural subsystem includes naturally occurring supplies of water and the hydrologic constraints they are subject to. Socio-economic subsystems capture the human activities related to the use of water which are, in turn, managed by and planned for in the institutional subsystem [4].

In this paper, the authors examine what a systemic approach to WRM might look like by analyzing some of the conceptual foundations and operational implications of a key WRM goal; resilience. Classically defined as the ability of an individual or system to persist in the face of perturbation, the concept of resilience has been around for decades and is utilized in a variety of domains ranging from psychology to ecology [5,6]. It is also a critical feature of WRM systems; especially given the societal urgency to make many infrastructure systems *more* resilient than they currently are. Despite its growing emphasis across domains, important questions remain as to what precisely is meant by 'resilience.' This uncertainty is more than just a function of variation associated with context specific applications of the idea. Questions about *what* is being preserved, for *whom*, for *how long*, and, even, *why* persist. Such questions are more than academic in nature. The answers to these, whether explicit or assumed, dictate the types of resilience strategies employed, how these interventions are measured, and, thusly, how success is determined. A systemic approach to WRM resilience, then, should begin with an analysis of the concept itself. Conceptual analysis, in turn, informs the operational definitions and parameters of the system. This foundation creates a basis for decision making at both a theoretic (e.g., modeling) and practical (e.g., strategic water planning) level.

There are two parts to the analysis presented here. In Part 2, the authors begin by categorizing several types of stresses exerted on WRM systems. Though some may be obvious, it is helpful to enumerate these in order understand what types of perturbations a WRM system must be resilient to. From here, the authors examine several definitions and dominant paradigms of resilience. This multi-faceted approach leads to the insight that resilience is a composite concept. That is, there are several significant properties that contribute to resilience. The authors go on to discuss the importance of scope, regarding both stakeholder identification and temporal horizon, in resilience. Part 2 includes a preliminary argument for adopting a social-ecological systems (SES) approach to resilience insofar as SES captures several of the key facets of the resilience paradigms profiled and maps well to water resource systems. Folke et al. define SES as "Integrated system of ecosystems and human society with reciprocal feedback and interdependence. The concept emphasizes the humans-in-nature perspective" [7] (p. 3). In Part 3, the authors outline how this conceptual foundation can be operationalized from a systems perspective. Specifically, several iterations of a qualitative equation of resilience are discussed. This leads into a discussion about how each term in the resilience equation can be measured (in the context of WRM). The authors explore several current measures in WRM and map these to the resilience properties which constitute the terms of the equation. Finally, the authors develop and discuss a preliminary causal loop diagram of water resource systems using the SES paradigm as a frame. Causal loop diagrams can be oriented around different phenomena—the one developed in this paper models the relationship between water supply and demand as well other influences in the system.

It is important to acknowledge that the idea of quantifying resilience is not a new one. Several tools have been developed in recent years to assess and promote resilience in one form or another; see [8,9]. Among other desiderata, the framework outlined here is intended to lay the foundations for a systems dynamics analysis of WRM resilience. This project, however, should not be viewed as a full-bodied alternative to existing tools but, ideally, complementary to them (or vice versa).

This paper is based on earlier work presented at a conference [10]. The resilience properties enumerated below, along with their mapping to metrics employed by water resource managers, constitutes a substantial extension of the systemic account called for in the conference presentation and paper.

2. Resilience Revisited

The section includes the enumeration and categorization of stresses that a water resource system is typically subjected to. If, at the simplest level, resilience is a response to stress, it is worthwhile to canvass the stresses faced by a water system in order to understand what a comprehensive approach to resilience requires. The authors then review several dominant resilience paradigms, distill out the properties reflected in the characterization of these paradigms, and then explicitly address the unavoidable normativity of resilience. This last aspect is important to emphasize for decision makers, especially engineers, who might cast their work as being wholly objective/scientific in nature and therefore overlook the tacit value assumptions of their work.

Before moving forward, however, a brief defense of the approach adopted here is in order. In surveying resilience paradigms, the intent is not to recreate extant literature; see for example [7,11,12]. Rather, the authors contend that, when combined, the emphases of individual paradigms support an inclusive, operationalized approach to water system resilience. That is, instead of treating these as mutually exclusive competitors, the authors suggest that each paradigm contains useful insights that can be combined towards a comprehensive approach to resilience in water resource systems. Key isomorphic similarities exist between the general paradigms discussed below and WRM specifically. The literature supports this. Quinlan et al. state "While multiple conceptions of resilience can be problematic in terms of common indicators and comparable metrics, they can also extend the concept to a broader spectrum of contexts and drive exploration for better approaches to implementation." [13] (p. 679). Furthermore, Martin-Breen and Anderies argue " ... although each framework has historical roots in particular disciplines, the frameworks themselves can be applied to any domain" [14] (p. 5). Finally, cross sectoral isomorphology has yielded interesting predictive insights in other domains; see Cantu and Beruvides analysis of similarities between cotton and lumber market behavior [15].

Some might argue that this bottom-up approach (i.e., beginning with conceptual foundations and building up from there) is needlessly classical, excessively academic, and without practical import. It is better, the argument continues, to begin with water resource systems as they are and work from there. While initially attractive in its immediacy and apparent practicality, such an approach risks the uncoordinated combination of multiple systems ideas or strategies. For instance, within the domain of engineering, several approaches to resilience prevail. Infrastructure resilience, for example, is sometimes defined as the rapid restoration of the pre-disturbance state of affairs [16]. Whereas some in water resource management have embraced SES resilience which does not privilege the original state of affairs so heavily [17]. Instead, SES allows that desirable equilibrium can take more than one form. Even within the domain of WRM, however, SES resilience is not universally or, at a minimum, explicitly recognized. The strategic water plan used to develop the operationalized approach outlined in this paper contains no mention of "social-ecological systems" or "social-ecological resilience" [18]. Even when it is recognized, water resource managers sometimes (arguably by necessity in many cases) focus on short term time horizons (several months to a year or two) versus longer term horizons (e.g., decades); see transformability discussion in [17]. This is meaningful insofar as the latter, longer horizons are significant in SES resilience. The variability exemplified here, then, can lead to less than effective outcomes or, worse still, counterproductive ones. The goal, in other words, is to move from a mosaic approach to a more systematic one; one that is ultimately systemic in its orientation. An early step towards this goal is to outline a theoretically informed, general operational approach that facilitates measuring and modeling resilience as a dynamic system characteristic.

2.1. Stress

To unpack the notion of resilience, it is useful to begin with a review of stress in a WRM context. The authors group these stressors into several categories with the understanding that some of the distinctions within the categories exist along a spectrum versus being fully discrete. First, water system stress can be either periodic or continuous. Storm events are an example of the former. A rapid increase of water in a system can lead to an increase of harmful bacteria in surface water and add strain to infrastructure (e.g., treatment systems); even given the boon of an increase in supply [4,19]. Periodic pressures can be subclassified by frequency (e.g., high versus low frequency). By contrast, the constant water draw-down from miscellaneous sectoral stakeholders including citizens, farmers, and businesses (energy companies, manufacturers, etc.) represents a continuous strain on the system. Population and economic dynamics determine whether this continuous pressure is constant or increasing; even the former can lead to a lack of resilience over the medium to long term. This distinction between constant and increasing pressures can be treated as a subclassification of continuous stress. Depending how one defines the temporal boundaries of the system, droughts can either be classified as a continuous or periodic stress.

Second, stresses can be both internal and external to the system. In addition to being periodic in nature, aforementioned storm events are external to the system itself. External stressors are, almost by definition, beyond the control of WRM decision makers and ought to be treated as exogenous parameters in corresponding models. Internal stresses include, again, stakeholder draw down as well as other instances such as a leaky (inefficient) infrastructure [20]. Not all internal stressors are necessarily within the control of water resource managers. For instance, if groundwater supplies are defined as part of a WRM system, the recharge rate (which is impacted by both natural hydrology and anthropogenic pressures) of an aquifer can be considered, with some exceptions, as being beyond the direct control of water decision makers specifically [21]. There is not, in other words, symmetry in the relation between periodic/external stressors and continuous/internal stressors.

The magnitude of the stress must also be considered. Not surprisingly, magnitude can be reckoned along qualitative lines (i.e., high, medium, and low) or on a continuous quantitative scale. For the sake of simplicity, the authors focus on the former in this paper. Though more coarse grained than a continuously defined magnitude, the high-medium-low approach lends itself to ease of implementation for water resource managers and other professionals; provided such markers (high-medium-low) can be scientifically established. Magnitude, arguably, can defined both objectively and relative to the resilience of the system. It is an important facet to understand when enumerating resilience properties; especially elasticity and stability.

Water resource managers have the unenviable task of trying to anticipate and design for stresses across these categories. The challenge is even more daunting given that combinations across categories create even more threats to system resilience. As highlighted by the storm example, a stress can be both periodic and high magnitude. This is distinct from lower level storms (e.g., those associated with a wet season) that are periodic but low magnitude events. Being aware of what category of stress one is designing for is important not only in determining the most effective strategy to address this stressor but also to identify gaps in the system's resilience. For instance, Easton and Beruvides developed a method for quantifying the resilience of power infrastructure based upon the modulus of resilience from materials engineering [22]. This approach is specifically intended to establish the resilience of power systems to high impact but low frequency stressors such as hurricanes. The approach does not, per the authors admission, address high frequency low intensity events. This is due, in part, to the latter being covered by infrastructure reliability versus resilience. This work illustrates that stresses on a system can be multi-faceted in nature and dictate different responses regarding resilience strategies.

2.2. Resilience and Related Terms

CS Holling [23] is credited with introducing the term resilience in ecology [12]. However, the term is not limited to this domain. Martin-Breen and Anderies state [14] (p. 5):

"Resilience has, in the past four decades, been a term increasingly employed throughout a number of sciences: psychology and ecology, most prominently. Increasingly one finds it in political science, business administration, sociology, history, disaster planning, urban planning, and international development."

Despite this tenure and ubiquity, however, there are some persistent ambiguities in the use of the term. The quote from Martin-Breen and Anderies continues: "The shared use of the term does not, however, imply unified concepts of resilience nor the theories in which it is embedded. Different uses generate different methods, sometimes different methodologies" [14] (p. 5). Gunderson notes, "Since most management actions are based upon some type of theory, these multiple meanings of resilience can lead to very different sets of policies and actions" [12] (p. 425). This variation reflects more than context-driven differences. Rather, some of it is attributable an incomplete understanding of the notion of resilience, ideological differences, and unavoidable constraints such as economics.

Martin-Breen and Anderies profile three resilience paradigms—what they refer to as engineering resilience, systems resilience, and resilience in complex adaptive systems [14]. Beginning with the first, engineering resilience as "bouncing back faster after stress, enduring greater stresses, and being disturbed less by a given amount of stress" [14] (p. 5). Similarly, Quinlan et al. borrow from Holling [24] to define engineering resilience as "a system's speed of return to equilibrium following a shock, indicating that a system can only have a single stability regime" [13] (p. 678). Angeler and Allen maintain that engineering resilience focuses on the rapid return to the structural *and* functional aspects of the system [5]. These characterizations appear to be largely informed by a structural-materials oriented approach in engineering; an interpretation reinforced by their choice of examples: Bridges, buildings, and infrastructure as a whole. Emphasis in engineering resilience is on the restoration of the state of affairs that preceded the perturbation. It is worth noting that this characterization of resilience is not a wholly static notion. Martin-Breen and Anderies do allow for the system to become progressively less sensitive to the original stress; as manifest by a decrease in distortion amount or, presumably, duration [14]. While the authors argue that this characterization of engineering approaches is unduly narrow, it does yield several useful insights. It, for instance, helps to highlight a couple properties of resilient systems. They demonstrate both a certain amount of elasticity and stability; where both can increase over time even as the system retains its normal state [14]. An additional property included here is the speed with which the system returns to its normal state. In this paper, this property is referred to as the retraction rate.

It is in systems resilience that the idea of the system itself changing over time is introduced [14]. Resilience in these systems can be defined as "maintaining system function in the event of a disturbance" [14] (p. 7). Here the emphasis is on preservation of system *function* versus its original structure. This conception of resilience also demonstrates an appreciation for the multi-level (e.g., stakeholder, spatial, and/or temporal scales) dynamism captured in systems-oriented approaches to resilience [7,11,12,25]. Accounting for multi-level interactions such as fast and slow feedbacks is critical viz. system resilience. This is especially true when decisions favoring short term, rapid feedback comes at the expense of overall system resilience [26]. At a minimum, the emphasis on function over structure characteristic of systems resilience is important because, fundamentally, it sets the criterion of success. Stated differently, it helps establish a broader stability domain and, by extension, thresholds [12]. These thresholds help identify critical points in the system that, when passed, can have deleterious, irreversible effects [7]. Thresholds also, the authors propose, acts as an important constraint on desired retraction rate; preventing undue emphasis on speed alone. The authors expand on this point in the next section.

Though the move away from an emphasis on the original state of affairs to the preservation of system function constitutes an improvement, Martin-Breen and Anderies maintain that it is still incomplete. They pose the question "If a government collapses, or becomes ineffective, does that mean a community can't be resilient?" [14] (p. 7). They go on to argue that communities can evolve over time; even in the face of a catastrophic collapse of the institutions they were previously dependent upon. This objection introduces a property of resilience that is thematic across several definitions—adaptive capacity (AC); see [27–29]. Adaptability (and transformability—more on this shortly) helps to define both ecological and social-ecological resilience [7,12]. Both ecological and social-ecological resilience fall under what Martin-Breen and Anderies refer to as complex adaptive systems [14]. Such systems are capable of adapting to stresses over time even fundamentally reorganizing. Folke et al. make a distinction between adaptation and transformation that helps capture the last point. Paraphrasing

Berkes et al. [27], they state "Adaptability captures the capacity of a SES to learn, combine experience and knowledge, adjust its responses to changing external drivers and internal processes, and continue developing within the current stability domain or basin of attraction" [7] (p. 2). Transformation, on the other hand, involves the more radical change from one stability domain to a new one [7]. While attractive for its flexibility, the authors focus on adaptability instead. The capacity for adaptation, then, is an additional property of resilience.

2.3. Properties of Resilience

The contention that the paradigms above are distinct but not mutually exclusive underlies the following observation—system resilience is a composite of several properties. These properties can be derived from the paradigms above and represent an early (viz. this project) attempt to move conceptual definitions into an operational domain. It is useful, then, to enumerate and describe these properties. Listing these properties explicitly can lead to a better understanding of the specific targets and outcomes of individual resilience interventions. That is, resilience interventions (aka "strategies") can be framed by their impact on one or more of the properties listed in this section. This, in turn, allows for an assessment of goodness-of-fit between intervention and the leverage point(s) in the system. Equally important, this connection between intervention and property also has the potential to identify unintended negative feedback loops, both reinforcing and balancing, when more than one resilience intervention is deployed simultaneously. Finally, the approach adopted here facilitates customization to a variety of different systems across multiple domains; especially where resilience is a central, critical goal. In enumerating these properties and identifying their corresponding water resource system measures in Part 3, the authors extend the structural-materials approach characteristic of engineering resilience. While such an extension is helpful, there are limits. It is important to keep in mind that systems resilience retains some *sui generis* features. There is a limit to the isomorphic connection between the structural-materials and systems domain in other words.

2.3.1. Stability

The application of stress does not entail that the system will distort as a result. Martin-Breen and Anderies' characterization of engineering resilience includes the possibility that a system may become less susceptible to a given stress over time [14]. That is, the same magnitude of stress applied at t_n may not affect the system as much as it did at t_1. This insight implies that systems have an activation limit; the authors refer to this as the system's "stability". It must be noted that this represents a departure from how stability is used elsewhere. As discussed in Gunderson, some authors use the term to denote when a system is at or near an equilibrium point [12]. Other conceptions couple stability and retraction rate. Some conceptions also take stability to imply the existence of only one valid stability domain. In this work, stability is used much more narrowly to denote the activation threshold a stressor must exceed to create a distortion in the system. If a stress falls below the limit represented by stability, then it does not cause distortion in the system. This lack of distortion may lead to the inclination to disregard stability in the context of resilience. That is, one might argue that resilience is concerned with what happens once the system begins to distort and not before. However, given that some resilience strategies are intended to increase this activation limit, it is worth including it in this typology. Moreover, strategies intended to promote stability may also impact other properties such as elasticity and thus warrant consideration.

2.3.2. Elasticity

Perhaps the most readily identifiable property corresponds to the magnitude of the disturbance the system can handle or absorb before failure. The corresponding system effect is distortion—so the concern more specifically here is with the amount of distortion a system can sustain before failure. Conjuring the image of rubber band, "elasticity" refers to the total distance the band can be stretched before breaking. This distortion can manifest in the system as a whole or with respect to one or more of its components. If a system is defined, in part, by the inclusion of certain necessary components, the failure of any one of these will then lead to overall system collapse. Goldberg refers to this property as "flexibility" and links it with what he refers to as "boundary-oriented" approaches to resilience [30] (p. 22). He appears to treat an emphasis on flexibility as being mutually exclusive with one that focuses on the speed-of-return to the system's pre-disturbance state. The authors do not go this far and so eschew the term 'flexibility' in favor of the intuitively appealing 'elasticity'.

It should be noted that in structural-materials science when a distortion is observable, it falls within the domain of "plasticity" versus "elasticity" [31]. Unobservable distortions fall within a material's elasticity range. This understanding of elasticity holds that as soon as stress is applied, there is a corresponding distortion; denying the notion of stability introduced above. Instead, elasticity constitutes the first significant threshold of the stress-strain relationship. Distortions that occur in the elastic region are temporary in nature—the material returns to its original state (e.g., geometry). Once a stress exceeds this threshold, then plasticity occurs. The distortion (deformation) observed in the plasticity range is permanent. Insofar as the deformation observed in a material's plasticity range is permanent, this term is inaccurate in the context of systems resilience where deformation as the result of stress is temporary [22,31]. The authors, then, opt to continue to use the term 'elasticity' but depart from the characterization that distortions in the elasticity range are unobservable. The contention that systems have an activation limit below which stress causes no distortion (observable or otherwise) represents another departure from the structural-materials approach.

2.3.3. Retraction Rate

If elasticity refers to the amount (distance) a system can distort as the result of stress, then retraction rate refers to the speed with which it returns to a state of dynamic equilibrium. Considering the characterization of engineering resilience above, this property is most germane to those circumstances in which the system returns to its original, pre-disturbance state. This property, for instance, is not necessarily applicable to those situations in which a system permanently changes (e.g., evolves) to a new status quo. Borrowing from both Folke et al. and Martin-Breen and Anderies, this latter rate may be referred to as 'transformation rate' [7,14]. It is worth pointing out that a faster retraction rate is not always favorable and may, in fact, come at the expense of overall system integrity. Goldberg, for example, observes that rapid, short term interventions intended to either maximize system output or, minimally, restore system equilibrium can lead to overall decline in system health [30]. The application of pesticides to crops serve as one such cautionary tale. An escalating, destructive cycle of pesticide application, pest resistance, and environmental degradation is the result, he contends, of a short-term emphasis on rapid system balancing [30]. In generalizing the lessons learned from this and other examples, he states [30] (p. 19):

"the decision-making process led to large-scale and rapidly implemented decisions. The system upon which such decisions were imposed reacted with unexpected consequences. These unexpected and often undesirable consequences resulted largely from the simplification of the system that is caused by large, fast, simple and direct decision-making process."

This is not to say that slower is always better. Rapid restoration to an original state may be desirable in some instances (e.g., the restoration of critical infrastructure); see [22]. This indicates that a nuanced approach to water system resilience interventions requires some recognition of what type of situation one is in. An unreflective emphasis on a rapid versus slow retraction or vice versa is counterproductive. This helps to highlight that individual resilience properties can either work in concert with or against each other.

2.3.4. Adaptive Capacity

The discussion of adaptation above leads to a fourth resilience property—AC. Whereas elasticity, retraction rate, and stability are anchored by the system's current equilibrium parameters, AC allows for the possibility of permanent system change over time; thereby enhancing its persistence.

When actualized, this capacity allows for system evolution while preserving its identity. Note, the authors treat "adaptation" as the actual manifestation of AC. The distinction between adaptation and transformation discussed by Gunderson and Martin-Breen and Anderies turns on what is being preserved (e.g., structure or function) [12,14]. If resilience is narrowly defined as preserving the original identity of the system, the distinction between adaptation (remaining within the original stability domain) and transformation (changing to another stability domain) is necessary. However, if the emphasis is placed on the continuity of a functionality that is equifinal in nature, the distinction between adaptation and transformation becomes much less important. The authors adopt the latter approach for the analysis in this paper.

2.3.5. Threshold

The idea that a system can be stable in the face of stress up to a point implies that there is a threshold beyond which permanent changes take place. This threshold is part of the literature on ecological and SES resilience [5]. "Thresholds are equivalent to tipping points and may be detected as discontinuities or bifurcation points in complex systems" [5] (pp. 619–620). Identifying this inflection point can provide helpful insights regarding system leverage as well as provide a necessary constraint to a prescribed retraction rate. The authors return to the latter point in Section 3.1.

2.3.6. Degradation

Some comments on acute vs. chronic distortion are necessary. Thus far, the assumption has been that each of these properties contribute to the preservation of system function, if not structure, indefinitely. However, it is important to recognize that chronic stresses may lead to the permanent degradation of these system properties. Returning to the rubber band metaphor, repeatedly stretching the band eventually leads to a reduction in the tension it can exert or its retraction rate. System design and engineering should take such medium to long term capacity degradation into account.

Quinlan et al. summarize the types of resilience surveyed in their article and authors adapt this approach to resilience types featured in this article [13]. Specifically, Table 1 orients around Martin-Breen and Anderies' literature review and summarizes the types of resilience profiled so far, the definition and characteristics associated with each, and the resilience properties derived as a result [14].

Table 1. Resilience Paradigms and Properties.

Paradigm	Definition	Major Characteristics	Properties
Engineering Resilience	The ability of a system to return to its original, pre-disturbance equilibrium after experiencing stress.	Emphasis on rapid restoration of original structure and function after perturbation. Increase ability of system to resist perturbation in the future.	Retraction rate, elasticity, stability
Systems Resilience	The preservation of system function over time and in light of a disturbance	Function emphasized over structure. A system may change structurally over time even as function is preserved	AC
Resilience of Complex Adaptive Systems	System evolves over time; even in absence of a disturbance	Self-organizing aspects of the system, multiple equilibria separated by thresholds. Includes SES	AC, Threshold

2.4. *System Identity and Scope*

The brief survey of definitions and characteristics above illustrates two key questions that should be addressed in aid of an informed, operationalized understanding of WRM resilience. First, it is crucial to understand what ought to be preserved in the face of stress. That is, what anchors the identity of the system intended to be resilient? Based on the simplified characterization of engineering resilience mentioned above, the answer appears to be that a system is equivalent to its structure and that the goal of this form of resilience is the rapid restoration of the original structure; the pre-stress condition [14]. If so, then it is incumbent on decision makers to identify the essential structural components of the WRM system and ensure they are preserved and, where possible, made more robust to various stressors. Other definitions above (e.g., systems resilience) shift the emphasis to function continuity (instead of structure) over time [5,14]. The additional assertion that complex adaptive systems, including SES, have multiple alternate equilibria, a clear expression of equifinality, would appear to reinforce the idea that it is the preservation of function specifically that ought to concern WRM managers [13].

The second key question that needs to be addressed relates to system scope; both in terms of considered entities ("stakeholders" for lack of a more accurate term) and temporal horizon. Choice of scope matters at an operational level both with respect to the dynamics given attention and gravitas as well with respect to identifying what constitutes success; specifically, the attribution of resilience. From the perspective of local decision makers, the lowest common denominator of a WRM system is likely to be current human users. This group can be further subdivided according to sector (e.g., agricultural, municipal, industrial) though even the most narrowly focused interventions for resilience are likely to include these and any other relevant human sector. This is social resilience [14]. Note, at the simplest level, this only captures current generations. More inclusive definitions of social resilience do demonstrate a concern for future generations but remain focused on human interests and outcomes exclusively. By extension, those approaches that focus exclusively on ecosystems can be referred to as ecosystem resilience. SES resilience incorporates both social and ecological dimensions. Though several of the authors discussed so far differentiate between social, ecological, and SES resilience primarily in terms of (1) the level of dynamism demonstrated, (2) presence or absence of multiple equilibria, and (3) emphasis on structure or function, it is natural to extend this to stakeholder identification [5,13,14]. Given this and the emphasis on slower moving variables, ecological resilience is characterized by a wholistic focus and, arguably, diminished emphasis on the welfare of discrete entities or even population subsets within the system. To be clear, slow-moving variables are those that can take decades to play out. In discussing lake system resilience, Carpenter et al. classify sediment phosphorous as a slow-moving variable [26]. In water resource systems, naturally occurring (vs. artificial aquifer storage/recharge) aquifer recharge can be a slow-moving variable [18,21]. These variables impact overall system stability but can present as background noise (at best) in system models with a time horizon shorter than the effect manifestation horizon.

Thus far, the focus of stakeholder inclusion has focused at the level of the system itself. However, Quinlan et al. and Matthews rightly maintain that this focus should not be exclusive [13,32]. Matthews frames it this way: "Do we fund projects that broadly build resilience for communities and ecosystems to reduce the impacts of climate change? Or do we ensure that *all* projects are themselves resilient to ongoing impacts, whether or not they provide broader resilience?" [32] (p. 15). Quinlan et al. observe that a shift to governance systems also involves a change from an analytical perspective to a "management or governance" perspective [13] (p. 684). Of course, the resilience of a system and the resilience of its governance cannot be neatly pulled apart; nor should they be. In WRM, if these two aspects are not fully inextricable, they are certainly mutually causally efficacious. Quinlan et al. recognize as much insofar as they point out that identifying the relationship between resilience strategies, including those focused on the system itself and those on system governance, can lead to "theoretically grounded, composite resilience indices and potential ways of comparing broader concepts ... " [13] (p. 684). Whereas traditional water management approaches emphasized supply and engineering solutions alone, integrated WRM sees that demand must be managed as well and that governance and education both have critical roles to play here [4,25,33]. This more comprehensive approach has been embraced by water resource managers with noteworthy outcomes [17,18]. Speaking about resilience without addressing education and governance, then, is incomplete. The operational framework proposed in the next section would create a mechanism by which these interventions can be assessed; both on their own and in combination with others intended to promote system resilience.

An operationalized understanding of resilience also requires specification regarding the temporal scope of the system. That is, the period of time over which the system needs to persist. The answer to this question dictates not only the stressors designed for but the determination of success. Identifying which stakeholders count will go some distance towards informing the relevant time horizon. Returning to the narrow focus alluded to above, if one is concerned with social resilience only, the relevant time horizon will, minimally, be the lifespan of current human stakeholders (e.g., years to a couple of decades) or perhaps one to two future generations; 50–100 years for example. A pivot to either ecological or SES resilience requires the incorporation of slower moving variables that can take decades if not centuries to play out. While this introduces greater complexity and uncertainty, such an expansion is essential given the impact such variables can have on WRM systems; climate change being a perfect example of this.

A persuasive case can also be made for linking a system's time horizon with what can be measured or modeled. This appears to be the implicit assumption when looking at both studies analyzing WRM dynamics and strategic water plans formulated at a municipal, county, and state level. Along these pragmatic lines, it is also worth considering the resilience implications of a temporal horizon set hitched to election frequency. Elections matter with respect to how water resources are managed. An official who promises lower taxes may meet this commitment by underfunding or canceling critical infrastructure improvements which can lead to a functional decrease in water supply and/or quality both of which, in turn, can stress a water system [20]. Not surprisingly, what emerges is the importance of temporal dynamics at several scales. A composite strategy should take all of these into account and is reflected in cross-scale resilience approaches [5,13].

The questions raised in this section have direct implications for the development of a systems dynamics model. For instance, the preliminary model in Section 3.3 below includes both human and non-human stakeholders. As the dynamics of consumption and supply availability are plugged into a future iteration of the model, a time horizon will need to be specified over which the resilience of the system is assessed.

2.5. Normativity in Resilience

There is an unavoidable normativity in the application of resilience thinking and interventions. This is so for a couple of reasons. Privileging the conceptions embraced by various stakeholders and decision makers assigns undue weight to approaches that are either incomplete or too narrow with regard to stakeholder inclusion and/or temporal horizon. In many instances, current practices are simply not up to the task. This, then, introduces the question: what *should* the goal be? Naturally, related questions regarding who/what should count and for how long follow. Moreover, resilience is, itself, not always a desirable outcome. Some individual and system level pathologies demonstrate a harmful amount of intransigence [13,14]. In the context of WRM, for example, a Tragedy of the Commons archetype can show deleterious persistence. This archetype is the result of overusing a shared, finite resource where the negative effects of such overuse are delayed. The feedback delay means that bad behavior can build inertia until the likelihood of resource depletion, if not exhaustion, increases substantially. Insofar as water is a commons, the conditions leading to the Tragedy are contraindicated if the goal is to have a sustainable water system. It is, thus, important to ask whether resilience is desirable to begin with. The authors contend that, prima facie, WRM resilience is fairly uncontroversial with respect to its desirability. Hence, this section will primarily focus on the following questions: who are the beneficiaries of the resilient system and for how long?

WRM are comprised of both human and natural systems. Interactions between these occur at multiple spatial and temporal scales. Moreover, the primary concern of both decision maker and consumer is the provision of supply (i.e., functionality) versus the particulars of how the supply is delivered. Indeed, as illustrated in the strategic water plan discussed in the next Part, the nature of this supply changes over time. It seems clear, then, that SES resilience is the most appropriate to apply within the domain of WRM. It captures the composite, dynamic, and adaptive aspects of water resource systems and recognizes the interaction between social and natural variables in a system. While the authors argue that the expedient return to an original system state (e.g., supply restoration after an outage) is appropriate to emphasize, this approach to resilience also concerns itself with meeting longer term, chronic issues as well. The authors contend that stakeholders in a water resource system are primarily concerned with the system's ongoing function to continuously supply water versus a particular structural arrangement. In theory, this flexibility also implies the possibility of multiple equilibria so long as water continues to be made available though Baehler and Biddle's study appears to indicate that decision makers involved in day-day resource management are more likely to favor adaptation within the current stability domain over the more radical transformations that lead to a new stability domain [17]. This emphasis on functionality is not to discount the role of structure; especially insofar as structure makes a given function possible.

The dual emphasis on social and ecological variables is a double-edged sword. Slow moving variables such as groundwater recharge, climate change, and others have clear causal implications for ongoing water availability and, therefore, ought to be accounted for when assessing a systems resilience to stress. The dynamics of such slow-moving variables can be complex given that they might either exert continuous but low-level pressure on a system or build, like a capacitor, and then impact all at once. This reflects the potential, albeit unavoidable, downside to SES models; increased complexity. Complexity is a potential downside for two reasons. First, an increase in complexity can also increase the potential for error, unintended model artifacts, and other concerns. Second, the more complex a model is, the less attractive it may be to decision makers who need tools that are accessible, reliable, and well matched to the available data [34]. Factoring in the welfare of non-human stakeholders both reflects an ethical mandate of SES resilience and further increases the complexity of this project.

Even the initial survey offered in this paper reveals an enormous amount of intricacy involved with conceptualizing and actualizing resilience. It may be tempting to sidestep the resulting difficulty altogether by arguing for a kind of prescriptive pluralism; to allow multiple definitions of resilience to be adopted and prescribed regarding a system and its governance. At an operational level this leads to an approach to measurement that is fractured and diminishes the benefit of the isomorphic application of insights from one domain to another. Thus, the authors reject this prescriptive pluralism in favor of a generalized approach that can be customized to different systems; not only in the domain of the commons resource management but beyond as well.

3. Operationalizing Resilience in Water Resource Management

While several thorny questions remain at the conceptual level of resilience, it is possible to move towards a more operational understanding in the context of water resource management. In this part of the paper, the authors lay the foundations for an operationalized approach to resilience in WRM.

3.1. Conceptual Equation

If, as has been argued, resilience is a composite of several properties, it is important to understand how these properties combine to create a resilient system. A simplified conceptual equation can be expressed thus:

$$\mathrm{R} = \mathrm{S} + \mathrm{E} + \mathrm{Tr} + \mathrm{AC}, \tag{1}$$

where:

R = Resilience
S = Stability
E = Elasticity
Tr = Retraction rate
AC = Adaptive Capacity

However, Equation (1) overlooks the role that system thresholds play. Furthermore, it does not consider Goldberg's observation that an overly fast retraction rate can create harmful disequilibria [30].

If true, an unrestricted retraction rate is not desirable. But what restricts the retraction rate? If an overly fast retraction rate takes the system out of its desired equilibria, it does so by passing one of the system's threshold points. The desired retraction rate can be thus framed as a rate constrained by the threshold point of the system.

$$R = S + E + Tr + AC, \tag{2}$$

where:

$0 < Tr < Threshold$

But this assumes that the threshold of the system can be identified and quantified. This requires a return to the questions of system identity introduced in Part 1. The authors acknowledge that precise identification is likely to be prohibitively difficult due to epistemic limitations. For instance, identifying a threshold in advance of it being crossed will be limited by the level of dynamism of the system. The more dynamic the system, the greater the potential difficulty in prognostication. Furthermore, while it is true that the threshold can more easily be identified once it has been crossed, if the system moves into a new stability domain, the original threshold value is no longer applicable. However, if resilience is anchored to system functionality versus structure, this may provide a practical, albeit imperfect, indicator of a threshold (e.g., a loss of functionality). Future iterations of this project will also need to clarify the relationship between a system's elasticity and its threshold. Prima facie, a system's threshold may be seen as the maximum point of its elasticity. This, however, warrants closer, future scrutiny and verification. This approach also assumes that the relationship between all of the properties is additive simpliciter. It does not account for interaction effects between the properties. Consider Distefano et al.'s contention that increasing interconnectivity leads to greater likelihood system shock propagation [35]. In the realm of water resources, if Municipality A incorporates a new source of water that Municipality B also depends upon, A will have increased the diversity of its supply portfolio but also made itself potentially susceptible to shocks in B (and vice versa). So, the equation can be updated to take these interaction effects into account:

$$R = (S + E + Tr + AC) + (PE) + (NE), \tag{3}$$

where:

$0 < Rr < Threshold$,
PE = Positive Interaction Effects
NE = Negative Interaction Effects

While Equation (3) offers a more comprehensive approach to resilience, it does not factor in the possibility of system degradation as the result of chronic system oscillations. At first blush, two strategies present themselves to address this. The first involves extending the constraints idea applied to Retraction Rate to the other terms in the equation. The second strategy treats system degradation as its own term in the equation. While the second approach is more coarse grained, it is also more elegant. For now, then, the equation can be updated using the latter approach:

$$R = (S + E + Tr + AC) + (PE) + (NE) - (D), \tag{4}$$

where:

$0 < Rr < Threshold$,
D = Degradation

Equations (1)–(4) all assume that each property is equally weighted viz. its contribution to (or detraction from as the case may be) resilience. However, it is possible that, in practice, certain properties (e.g., elasticity) may be more important to a system's resilience than others (e.g., stability). Introducing a weighting factor for each property in the equation allows for a more nuanced approach and creates a pathway to determine where the most leverage in a system occurs. This updated equation would be as follows:

$$R = (\delta S + \lambda E + \gamma Tr + \kappa AC) + (PE) + (NE) - (D), \quad (5)$$

Note, these weighting coefficients need to be determined through empirical analysis. For the time being, the authors assume that $\delta = \lambda = \gamma = \kappa = 1$.

3.2. Measuring Resilience

Having established that resilience is a composite of several properties, it is now worthwhile to consider metrics that correspond to these. That is, it is important to look at how resilience is measured. Given that the goal is identify an operationalized approach to resilience, the authors examine the kinds of data and metrics currently utilized by water resource managers. More specifically, the authors review the 100-year strategic water supply plan for the City of Lubbock, Texas; a municipality located in a semiarid region of the southwestern U.S. [18]. This focus on currently available data is informed by the assumption that the easier it is to defensibly measure resilience, the more likely it is to be incorporated into the planning and decision-making process. This is not to foreclose on the development of new metrics to augment decision-making. Rather, it is to emphasize that resilience must be practical to be incorporated into WRM.

This emphasis on currently available data has a potential drawback, however, inasmuch the fit between metric and resilience property may not be a perfect one. Moreover, it is possible that one metric may correspond to more than one property. The mapping between metric and property in this section, then, should be seen simply as a *start* towards an operationalized approach to resilience. Two further caveats are necessary. First, given that the interaction effects discussed in conceptual Equations (3) and (4) are currently framed as the relationship between the individual properties, the authors assume that it is not necessary (at this stage) to identify a separate metric just for the interaction effects themselves. That is, identifying the metrics corresponding to properties will be enough. Second, while it is hypothesized that chronic stresses will lead to system degradation over time, this needs to further explication and analysis. Degradation effects, then, are put aside in this section. A summary of the connection between the resilience properties and metrics currently utilized in the strategic water plan is included at the conclusion of Section 3.2 in Table 2.

Table 2. Resilience Properties and Metrics.

Property	**Metric(s)**
Stability	Difference between PDD Capacity and Actual PDD
Elasticity	Difference Between Current Annual Supply and Demand Difference Between Projected Annual Supply and Demand
Retraction Rate	Modified Resilience Index for HILF To be determined for chronic stresses
AC	Availability of Additional Supplies of Water Availability of Conservation Practices/Capacity for Behavioral Change

3.2.1. Peak Daily Demand

Water utilities must make sure that they can not only provide enough supply to meet demand on annual basis, but that they can accommodate peak usage rates at any given moment in time. In the Lubbock Strategic Water Supply Plan (LSWSP), this peak demand is known as Peak Daily Demand

(PDD). PDD, measured in millions of gallons (mg), is the product of Average Annual Demand (AAD) and a Peaking Factor (PF) [18] (pp. 41–42). Thus, the equation for PDD is:

$$\text{PDD} = (\text{AAD})(\text{PF}), \quad (6)$$

where AAD = (Annual Water Demand/365 days)

PDD reflects the state of the city's infrastructure. Is it reliable, adequately developed, and maintained to an acceptable standard? So long as the city remains at or under its PDD, it can meet demand at any given point of time given the adequacy of current supplies. Extending this to the resilience literature, then, the authors argue that the difference between the PDD the system is capable of and the actual PDD corresponds to the stability of the system. If capacity exceeds demand in this domain, the system is stable. If the demand exceeds capacity then, on a short-term scale, this translates into lapse of services to stakeholders. Momentary lapses do not necessarily mean the demise of the system though it does indicate that the system is now under active stress that will test its elasticity and AC. Protracted shortfalls between peak capacity and demand, however, will be problematic.

3.2.2. Difference between Annual Supply and Demand

If PDD is a measure of a water system's stability, it is natural to suggest that the difference between annual supply and demand corresponds to the system's elasticity. When the supply outstrips demand, the system retains some measure of elasticity. When annual demand outstrips supply, the system moves into a fragile state which, if not corrected, will lead to its collapse. This correlation between annual supply/demand accounts for both acute and chronic categories of water system stress (e.g., storm events and drought).

The LSWSP measures both current supply and demand as well as projects future supply and demand. Demand is a function of population growth as well as consumption rates. For instance, Lubbock is not a large city when compared to metropolitan areas such as New York City or Chicago. However, it has a strong agricultural component that accounts for significant water usage. Not surprisingly, then, supply is a function not only of volume of water available but the rate of consumption. Supply and demand are both dynamic concepts with an unavoidable amount of uncertainty. This uncertainty, then, propagates into assessments of a system's resilience.

The current difference between supply and demand provides a snapshot of the system's current resilience. Often, however, the interest is ensuring resilience over the long term. Thus, the projected difference between supply and demand becomes a central focus of assessing a system's elasticity over time. While this delta between supply and demand provides a nice, single focus, measuring it can be complex. On the supply side, this means first characterizing the sources of water available. In the case of the LSWSP supply is a composite of surface water, ground water, and reclaimed water. Each source is subject to a variety of dynamic constraints. For instance, the City of Lubbock has become more reliant on groundwater sources over the past 27 years; especially in the last seven [18]. Unless withdrawal rates are at or under recharge rates, this source of water is finite and so cannot be considered a permanent contributor to a system's flexibility (depending on the time horizon adopted). Surface water is, in a basic sense, renewable but more sensitive to exigencies such as drought and other climate change related effects. These and other constraints, then, make measuring elasticity a more difficult proposition. This difficulty is compounded when uncertainties regarding demand projection are taken into account. The LSWSP, for instance, bases its population projections in U.S. Census data and is thus susceptible to the flaws and assumptions associated with this tool. To account for some of these uncertainties, the LSWSP enumerates several scenarios when anticipating annual demand [18]:

$$\text{Expected Drought Demand} = (\text{Expect. Pop. Growth})\ (\text{Drought Consumption}), \quad (7)$$

$$\text{Conservation Demand} = (\text{Expect. Pop. Growth})\ (\text{Conservation Demand}), \quad (8)$$

$$\text{Accelerated Growth Demand} = (\text{Accel. Pop. Growth})\ (\text{Conservation Consumption}) \tag{9}$$

A similar exercise is involved in anticipating the types and amounts of water available. This leads to an interesting question regarding resilience—which combination of scenarios ought to be used when assessing elasticity? If elasticity is seen as the system's total distortion capacity, this would argue for adopting worst case scenario thinking. In the case of water resources, this would entail the unfortunate combination of maximum demand (population and consumption rates) and minimum total supply. Note, however, that while Equation (9) comes closest to this by assuming accelerated population growth, it also adopts a "conservation consumption" rate. In characterizing this rate, the LSWSP states " ... water demands are not mitigated by successful conservation efforts and is what would be expected under severe drought" [18] (p. ES-13). Further exploration of this assumption is necessary to ensure that expected consumption during drought reflect worst-case scenario thinking in order to establish the system's elasticity insofar as this is defined by the maximum capacity to stretch in response to a stress. Understanding elasticity, in other words, requires an understanding of the upper limits of the system. In the case of water systems this means examining worst-case scenarios.

The near-term takeaway is that the difference between supply and demand is a useful, elegant place to begin when both measuring a system's current elasticity and projecting future values. However, background assumptions need to be made explicit. Additionally, elasticity measures should involve an error factor that is incorporated into the assessment of overall system resilience.

3.2.3. Retraction Rate

Prima facie, identifying a single metric that corresponds to retraction rate in water resource systems is a difficult proposition. The Resilience Index developed by Easton and Beruvides provides some initial cues on how to proceed, however [22]. As pointed out earlier, they focus on high impact low frequency (HILF) events such as hurricanes that lead to power outages; especially protracted ones. Resilience, then, is framed as the duration of an outage and the percent of customers without power where the goal, understandably, is to minimize both the number of people affected and duration of outage [22]. This approach to resilience reflects the aforementioned emphasis on the rapid restoration of the system to its pre-disturbance state of affairs. Adapting it to water resource management, a loss of water services would be the stand in for power outages and the percent of the population affected would remain the same. This adaptation has some precedent insofar as percent of population with access to water is used as one measure of sustainability in water resource systems; though the emphasis is on those who chronically lack access to safe drinking water versus those who have lost access as the result of an acute event [29]. The successful adaptation of the Resilience Index would go some distance towards measuring retraction rate in water resources. Initially, this would lend itself to quantifying retraction rate under HILF stresses placed on water resource systems. Adapting the Resilience Index to chronic stresses may be more challenging. Water systems must also address high frequency, low impact events that can, nevertheless, lead to failure over time. This challenge is made more complex given the contention that, under certain conditions, the retraction rate should be constrained by threshold values.

Rather than focus on identifying a single, all-encompassing metric, it may be best to use one retraction rate measure under HILF conditions in which rapid restoration is desirable and another to capture the rate under chronic stress conditions constrained by the systems threshold values. More research needs to be done in this regard.

3.2.4. Adaptive Capacity

A sufficiently complex adaptive system will have a wide variety of ways to respond and grow as the result of stress. Identifying all the metrics that correspond to these is a project in and of itself. In the context of water resource systems, a good place to start is with the availability of additional sources of water as well as the capacity for more efficient management of current sources. Beginning with the former, AC can be measured in part by identifying the amount, type, and ready availability of new water. So, in a region like Lubbock, this involves taking stock of undeveloped wells in water fields and other ground water sources and locating new sources of surface water. This aspect of AC is, of course, guided by hydrologic, political, and economic constraints. For instance, one source of water currently used in the LSWSP is approximately 150 miles away and shared by other municipalities [18]. Thus, allotment, transportation, and treatment considerations all constrain this source of water. AC is also a function of the percentage of water than be reclaimed and circulated back into the system. Finally, infrastructure improvements can recover “lost” water thus bolstering the supply. The amount an infrastructure can be improved in terms of capacity can also be measured and summed into a system’s overall AC. These all focus on supply side considerations.

The capacity for behavioral change (i.e., modification on the demand side of water) can also be measured and treated as part of the system’s AC. More specifically, if current consumption rates can be reduced through the adoption of water conservation practices (as seen in Lubbock), the amount they can be reduced by can be measured as water saved. This amount can be factored into calculation of AC. Governance, once again, has a strong role to play in building—here with regards to AC. Referring to earlier work [36], Pahl-Wostl highlights the importance of “multi-level interactions, polycentric system architectures and the interplay between formal and informal networks" [25] (p. 2925). These interactions, architectures, and networks help define the demand side agility of the system while also having significant implications for supply side management as well.

AC in a water system, then, can be treated as a function of both the availability of new water sources (which can be quantified), infrastructure improvements, and behavioral changes. This approach to AC focuses exclusively on active interventions. Certain systems, especially natural ones, also demonstrate passive or automatic AC. Examining such strategies will be the focus of future research.

3.2.5. Threshold

As characterized in this paper, the threshold of a system is not a resilience property per se but a boundary condition(s) that acts as a constraint on at least one of these; retraction rate. Given this role, then, it is important to discuss how threshold might be measured; especially considering the epistemic limitations alluded to above. The discussion of stakeholder identification and time horizon in Section 2.4 and application of SES resilience prescribed in Section 2.5 will provide some guidance here. More specifically, threshold can be measured by looking at the number and type of stakeholders treated as part of the system as well as the relationships between them. Threshold can also be measured by looking at the time horizon used to define and monitor the system in question. Measuring threshold in this way provides a frame for assessing and, ultimately constraining, the system’s retraction rate. If, for instance, an intervention overly focused on the quick restoration to the original state of the system spells long term fragility (within the chosen time horizon) or excludes essential stakeholders in the process, it should be rejected in favor of a slower rate [26,30].

The LSWSP is concerned with ensuring the provision of water services for human stakeholders over the next 100 years [18]. If the argument in Section 2.5 is sound, such an approach is incomplete. If it is best to apply SES Resilience to water systems, non-human stakeholders and ecological dynamics must be considered as well. Moreover, while a 100-year time horizon easily meets the definition of “long term thinking” in traditional human terms, it is, arguably, not long enough to take into account some of the slower moving ecosystem variables that will, given a short time horizon, manifest as background noise in the system. These slow-moving variables, however, have significant impacts on long term resilience. The LSWSP certainly considers some of these dynamics (the impact of certain plants on water quantity, drought conditions, etc.) but is incomplete regarding stakeholder inclusion. It must be acknowledged that 100 years also stretches many of the modeling/prognostication tools available to decision makers and so it is understandable why it is adopted as a de facto upper limit on strategic planning. This limitation provides some impetus to identify and implement resilience interventions that do not depend on accurate forecasting or, at a minimum, are successful under a range of possible conditions.

3.3. The Dynamics of Resilience

Resilience is, at its core, a dynamic concept. Not in terms of how it is defined (though this is currently true viz. its status in the literature) but intrinsically. Resilience is a dynamic reaction to dynamic stresses as well as the capacity (at a minimum) of a system to change over time. Furthermore, if resilience is indeed a composite of several properties, interactions between these properties add a layer of dynamism. Finally, water resource systems are comprised of complex interactions between natural, economic, political, psychological, and technological components. An operationalized approach to resilience should take all of this into account. The authors assert, then, that systems dynamics is not only helpful but essential to the goal of making water systems more resilient.

The metrics proposed in Section 3.2 center on the relationship between water supply and demand. This reflects not only the focus of strategic water plans like the LSWSP but the idea that water is a commons resource. Avoiding Tragedies of the Commons requires the proper management of the supply-demand relationship over time. Building on this and incorporating several of the stresses enumerated in Section 2.1, the authors propose the following preliminary causal-loop diagram (CLD), developed using Vensim 7.2a, in Figure 1, below.

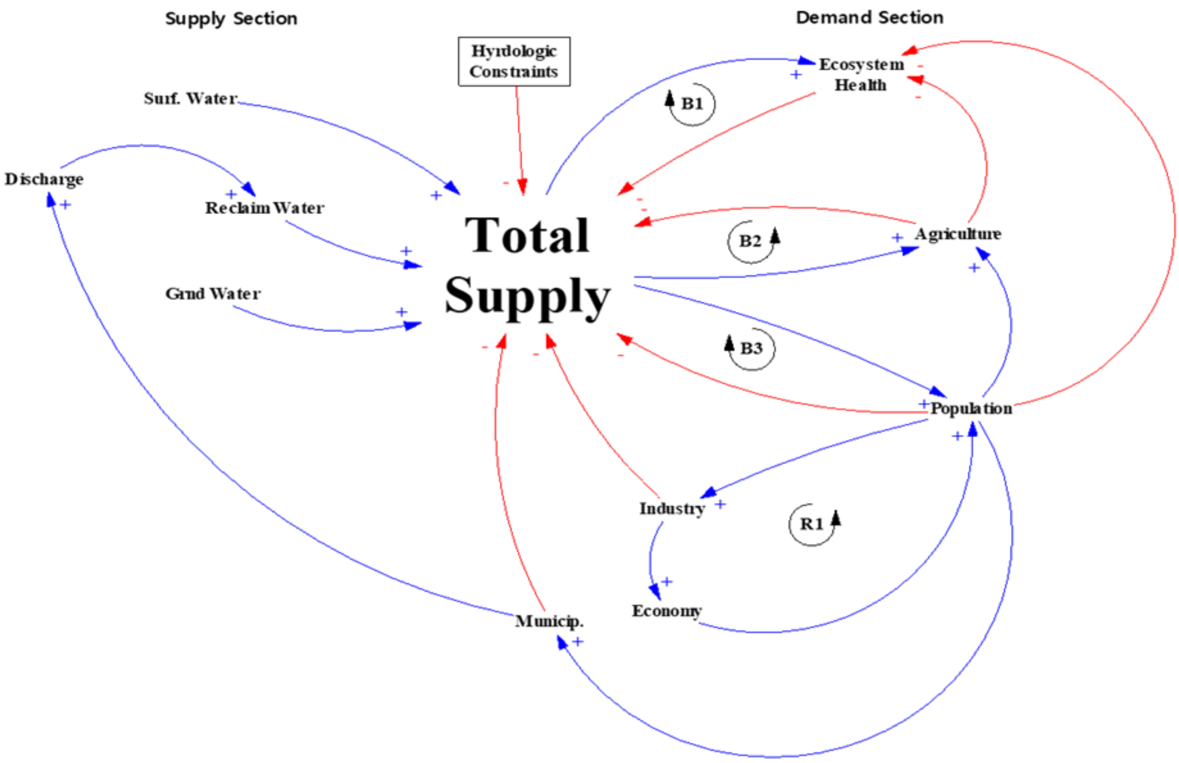

Figure 1. SES Causal Loop Diagram of Water Resource Systems.

In its current form, this diagram treats Total Supply as the stock of the system. Per the figure, each source of water on the left-hand side is an incoming flow that increases the total system stock. Each of the variables on the right-hand side represent a source of demand and therefore outflow with respect to the Total Supply. Resilience is, thus, a function of the system's current stock and the flows that affect it (stock). It is worth noting that water sources can also be portrayed as stocks themselves; not strictly as flows. Groundwater, for instance, can also be framed as a stock affected by inflows (recharge rates) and outflows (pumping rates). Deriving stock-flow relationships from this CLD is a natural and necessary extension of the model. Initial balancing and reinforcing loops have been labeled. These reflect a generalized mental model of the system but are likely to require modification both with the development of this model and, at a minimum, the addition of system specific details (e.g., agriculture plays a bigger role in some systems than others which has system dynamic implications). This modification is made more likely given the variable nature of water systems. Subsequent, empirically informed iterations of the model will bear out the actual nature of the feedback loops in a particular system. This is especially true in the case of balancing loops where it is necessary to establish the magnitude of influence over a defined (and defensible) time horizon in each direction. What appears to be a balancing loop now may be otherwise if one direction of influence overpowers the other within the model's time horizon.

Several initial assumptions were necessary regarding the supply side of this diagram. First, it is assumed that increases in discharge from municipalities increase the amount of water available for reclamation. Of course, if the water is not reclaimed, at least in the short term, the causal connection is more tenuous. An alternate method of capturing the dynamic would be to include causal lines from both surface water and ground water (i.e., an increase in either source leads to at least a potential increase in the amount of water available for reclamation). Future versions of this model should clarify the intuitively plausible claim that an increase in reclaimed water usage will lead to decreases in both surface and ground water usage. This has implications for the resilience of the system. It is also assumed that the water reclaimed will come from both ground and surface water supplies. However, the actual composition of surface and ground water sources will vary between and even within water systems. Second, this diagram does not factor in artificial groundwater recharge. A finer grained model should incorporate the impact of artificial recharge efforts (e.g., storing water surpluses in aquifers to be drawn later during periods of higher demand); see [18]. Note that Figure 1 also does not include any feedback delays. As discussed earlier, such delays are an essential feature of the Tragedy of the Commons archetype and plague water resource systems in particular (e.g., water budgeting). Here again, a more complete approach to modeling water resource management as a SES will include delays. These delays can be determined based on existing data and model outcomes.

The right side of the diagram incorporates several of the most common sources of demand in a water system. It (diagram) builds on the assertion in Section 2.5 that water systems resilience is best framed using a SES model. Among other requirements, this means incorporating both human and non-human stakeholders (Ecosystem Health). It is important to be clear about the normative force of this inclusion. Ecosystem Health is not seen merely as a source of supply pressure. Rather, a healthy Ecosystem is also seen as a feature and goal of a resilient water resource system. One assumption included in this diagram is that, at least in the near future, increases in human population will have deleterious impact on Ecosystem Health. A more harmonious relationship should be pursued but until then, resilience requires a more realistic picture of the dynamic between these variables. The authors also assume that an increase in Ecosystem Health will not cause any change in Population size. Here again, however, it is possible that humans will find flourishing ecosystems more attractive in the future; actively seeking them out (leading to population growth). The inclusion of Ecosystem Health, along with Hydrologic Constraints, also goes some distance towards addressing questions about time horizon. Both Ecosystem Health and Hydrological Constraints include fast and slow-moving variables. Each of these must be accounted for in assessing the current state of the system as well in moving towards a more resilient state in the future. Hydrologic Constraints are treated as an exogenous parameter here. In this model, this parameter includes the dynamics associated with the current hydrologic cycle, changing climate conditions, and other conditions. Here too, greater specificity will be needed to explore the individual and combinative effects of each of these sources of exogenous pressure. By contrast, political dynamics such as the impact of election cycles on decision making and, eventually, supply and demand, are not explicitly identified. Rather, in this diagram they are treated as being part of human stakeholder variables such as Municipalities, Agriculture, and Industry. A final comment is necessary regarding the Ecosystem Health variable—this model groups flora and fauna together. Typically, however, plants (flora) are more impactful on a water supply and, therefore, resilience than animals (fauna) are. Future models should parse these components out in order to capture the dynamics of an increase in flora versus fauna. Additionally, a closer look at the specific biome that the water resource system is located within is critical to understand the relationship between Ecosystem Health and Total Water Supply. In this diagram the relationship is portrayed as being inverse (comparable to the relationship between Population and Total Water Supply). However, in the case of some ecosystems, an increase in flora specifically may lead to a net increase in Total Water Supply.

Water usage is a function of both population size and per capital consumption. As indicated earlier, areas with small to medium populations can nevertheless experience high water demand depending on the kind of sectoral activity they support. The diagram reflects this by linking population to growth of water consumption in municipalities, industry, and agriculture. Additionally, increases in each of these sectors leads to a decrease in Total Water Supply.

Despite the number of variables and connections modeled in Figure 1, it still represents a fairly course grained approach to complex water systems. Even still, it provides a starting point for the number of variables that need to be considered when assessing resilience. The variables identified are simultaneously sources of and susceptible to the stresses outlined in Section 2.1. Additionally, the diagram represents a visual answer to the questions of resilience of *what*, for *whom*, and for *how long*? When coupled with the metrics identified in Section 3.2, this outlines how resilience might be operationalized.

4. Conclusions and Future Research

Despite its ubiquity across domains and time, resilience has remained a difficult concept to fully define and implement. This difficulty notwithstanding, it remains a critical goal for water resource managers faced with balancing multiple demands from multiple stakeholders. Moving towards this goal requires conceptual precision which in, turn, makes operationalized approaches more likely and defensible. Hoping to facilitate such movement, the authors surveyed several paradigms of resilience with an eye towards identifying the core features of resilience. Resilience, it is argued, is a composite of several properties: stability, elasticity, retraction rate, and adaptive capacity. A full conception of resilience should also capture interaction effects between these properties as well as account for system degradation over time. The properties help identity *what* should be measured. In striving for resilience (and/or assessing its current a system's current state), water managers must also determine *who* the system is being made resilient for and for *how long*. The authors contend that a social-ecological approach to resilience provides answers to both of these questions.

This conceptual framework sets the stage for an operationalized approach to resilience in WRM. The resilience properties enumerated above can be mapped to current measures commonly used by decision makers. While an imperfect match, the scheme proposed in this paper does provide a starting point in terms of resilience assessment. Finally, mapping the system using a causal loop diagram helps to identify essential relationships between variables that constitute water resource systems. Insofar as each of these is necessary to a healthy, resilient water resource system, they must be factored into assessment tools; especially given that, at its core, resilience is a dynamic goal.

The analysis in this paper sets the stage for a more detailed model of resilience. This model will need to incorporate cross-scale resilience considerations regarding stakeholder identification, fast and slow-moving variables, and the relationship between these [5,13,14]. This includes but is not limited to capturing the dynamic effects of broad, complex phenomena such as global climate change as well as the nearer term effects of social decision making. This also highlights the importance of quantifying the interaction effects between resilience properties. Establishing the pathway and measure of these effects will be essential to avoiding a mosaic approach to resilience that ends up implementing interventions that work at cross purposes with each other or otherwise lead to a net reduction in resilience. Coordinating interventions (aka "strategies"), in turn, requires a look at the relationship between these and the properties enumerated in this paper. The authors also acknowledge that the list of properties here may be incomplete. One might wonder, for example, whether the rate of adaptation should be assessed in addition to adaptive capacity.

Finally, making water systems resilient (or more so if they already are) may entail looking outside of these systems for sources of strategies. More specifically, there is growing appreciation for the resilience demonstrated by a variety of natural systems. Unsurprisingly, water scholars and decision makers have begun to look to nature for system design inspiration. This biomimetic approach holds great promise for WRM but must be informed by economic parameters and contextual clues from the natural environment.

The operationalized approach here is best viewed as a beginning—an attempt to bridge conceptual paradigms and practice. A survey of existing resilience tools will be helpful in developing this approach further. Tools like the Climate Risk Informed Decision Analysis (CRIDA) developed by Mendoza et al. have an important role to play in resilience goal setting and assessment [9]. The approach here should be informed by and possibly combined with such tools in aid of a quantitatively rigorous approach to resilience. A secondary desideratum of this project is to develop an operationalized approach to resilience that can be generalized to other domains; whether in commons resource management or beyond.

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Abbreviations

The following abbreviations are used in this article:

AAD	Average Annual Demand
AC	Adaptive Capacity
CLD	Causal Loop Diagram
CRIDA	Climate Risk Informed Decision Analysis
CoBRA	Community Based Resilience Analysis
HILF	High Impact Low Frequency
IPCC	Intergovernmental Panel on Climate Change
LSWSP	Lubbock Strategic Water Supply Plan
mg	Millions of Gallons
PDD	Peak Daily Demand
PF	Peaking Factor
SES	Social-Ecological System
WRM	Water Resource Management

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