

Article

A Framework for Developing a National Research Strategy for Water Reuse

Arkalgud Ramaprasad ^{1,*}  and Thant Syn ² ¹ Information and Decision Sciences, University of Illinois at Chicago, Chicago, IL 60605, USA² Department of Information Systems, Analytics & Supply Chain, Florida Gulf Coast University, Fort Myers, FL 33965, USA; tsyn@fgcu.edu

* Correspondence: prasad@uic.edu; Tel.: +1-(312)-485-1378

Abstract: Water reuse is critical to national development, sustenance, and survival in this era of climate, demographic, and social changes. There is no systemic national approach to systematically addressing this challenge. This paper presents a framework and method to develop a national research strategy for water reuse. It presents an ontology of water reuse strategies that encapsulates the combinatorial complexity of the problem clearly, concisely, and comprehensively. Subsequently, it discusses the method to use the framework to develop a national strategy, adapt it through feedback and learning, and ultimately effect a revolutionary change in the strategy for water reuse.

Keywords: water reuse; ontology; ontological framework

1. Introduction

“In practice, all the water on the planet is eventually reused” [1] (p. 5). The long-term global transportation and transformation of water for use and reuse transcends geographical boundaries. However, to assure daily water security, public health security, and ecosystem resilience for stakeholders, this transportation and transformation must be managed and controlled internationally, nationally, regionally, and locally. For instance, the reuse of municipal water in the U.S. could potentially increase the nation’s available resources by approximately 6% of total water use [2], while water conservation could reduce household water use by more than 30% [3]. Hence, there is a need for a national research strategy for water reuse.

There is a rapidly growing body of literature on water reuse. As of 13 November 2023, there were 1846 papers with ‘water reuse’ in their title indexed in the Scopus database, covering many countries. This corpus excludes papers that address water reuse in their content. There is also a large, growing corpus on the subject not indexed in Scopus. Despite this large volume of research, there is no clear, concise, and comprehensive framework to guide the research to address the challenge. There is no ‘Google Map’ for research on water reuse.

Tzanakakis et al. [1] conducted an extensive review of the literature and listed the following knowledge gaps in water reuse research:

1. Possible interactions of agricultural reuse with soils, plants, and crops;
2. Fate of organic microcontaminants in receiving environmental media and targets;
3. Epidemiological risk of antibiotic-resistant bacteria and/or resistance genes released in the environment with treated effluents;
4. Issues concerning climate change and/or variability;
5. Strategies to overcome barriers to water reuse;
6. Links among reuse schemes, ecosystem services, and SDGs.

These are significant gaps, and there may be many more. We shall not know the missing gaps without a framework to map the corpus. There may be pathways for water



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reuse that have been effective and must be reinforced, those that have been ineffective and must be redirected, and those that have been untested/unknown and must be researched.

Almost all countries today are being compelled to address the challenge of water reuse by the changes in their demography, climate, economy, industry, sociology, and other similar factors. There is a need for a systemic framework to systematically guide countries' national research strategies for water reuse. This framework must help systematize local research, localize global research, and globalize local research. We present an ontological framework for developing a national research strategy for water reuse.

An ontology is an organization of the terminologies, taxonomies, and narratives of a problem that can be conceptualized as a scientific theory of the problem [4–7]. As a scientific theory, it can be used to describe, explain, predict, and control [8] water reuse through feedback and learning [9,10] systemically as part of a broader ecosystem, and systematically by exploring the innumerable pathways within it. Ontological frameworks have been used to study river water sharing [11], national healthcare policies [12–16], design thinking [17], public health informatics [18], local climate change [19], and other domains. In the following paper, we (a) present an ontology of water reuse strategies based on the present definitions of water reuse, (b) discuss how it can be used as a comprehensive, national research design framework, and (c) delineate its implications for research on, policies for, and the practice of water reuse.

2. The Ontology of Water Reuse

Water reuse is a complex combinatorial problem. Its many definitions simplify the problem and address only parts of it and not the whole. A coordinated national research strategy for water reuse must address the combinatorial complexity systemically and systematically.

The Ontology of Water Reuse Strategies (Figure 1) will be used to do so. It incorporates the key terminologies and taxonomies of water reuse strategies from the Water Research Foundation (WRF) research projects (<https://www.waterrf.org/research>, accessed on 13 November 2023), the associated workshops, the 1846 global papers with 'water reuse' in the title indexed in Scopus (as of 13 November 2023), and other related literature. This ontology, after validation by stakeholders, can serve as the framework for developing a coordinated national strategy for water reuse. It is described below.

2.1. Water Reuse

'Water Reuse' at the center of the ontology is defined as a combination of the sources of water (Figure 1—Source), processes of reuse (Figure 1—Process), and end uses (Figure 1—End Use) of water, denoted by the taxonomies in the three columns. Each taxonomy is based on the current literature and its elements are reasonably mutually exclusive and sufficiently exhaustive. We shall discuss each in detail.

2.1.1. Sources of Water

A major part of the taxonomy of sources of water is based on the classification by Hayek et al. [20] (p. xii). They classify water sources as traditional and alternative sources. Further, they classify traditional sources as surface and groundwater. We have reorganized and extended their list of alternative water sources. We have grouped condensate, foundation drainage, and rainwater under buildings as a source. Similarly, we have grouped domestic wastewater and graywater as alternative domestic sources. Stormwater has been retained as a separate alternative source. We have refined the sources of processed water as follows: industry, agriculture, oil and gas, and hydro power [1,2,20–23]. Agriculture sources have been further classified as irrigation, livestock, and aquaculture [1,2,20–23].

The qualitative and quantitative properties of these sources of water are different. They are also likely to be different based on the geographical location, annual season, and other spatio-temporal factors. These sources must be separated, differentiated, integrated, and combined for effective water reuse.

Scope	Action			Water Reuse			Stakeholder	Outcome
	Agent	Impetus	Scale	Source	Process	End Use		
International	⊕ Policy	⊕ Driver	Centralized	[system for] Traditional	[water] Rejection	[for] Potable	[use by] Government	[for] Public Health Security
Federal	Legislative	Norm	Distributed	Surface	Reclamation	Direct	Utility	Prevention
State	Economic	Barrier	Onsite	Ground	Recycling	Indirect	Industry	Detection
Tribal	Regulatory			Alternative	Reuse	Surface	Citizens	Reporting
Local	Fiscal/Financial			Building	Residue	Aquifer	Nature	Response
	Informational			Condensate		Groundwater		Systems Management
	Contractual			Foundation Drainage		Non-potable		Norms Management
	Legal			Rainwater		Domestic		Risks Management
	Social			Domestic		Toilet Flushing		Water Security
	Technology			Wastewater		Fire Protection		Availability
	Collection			Graywater		Air Conditioning		Accessibility
	Processing			Process Water		Process Water		Quality
	Storage			Industry		Industry		Equity
	Distribution			Agriculture		Agriculture		Sustainability
	Comm./Outreach			Irrigation		Irrigation		Ecosystem Resilience
	Human			Livestock		Livestock		Recognition
	Digital			Aquaculture		Aquaculture		Resistance
	Workforce			Oil & Gas Water		Oil & Gas Water		Response
	Labor			Hydro Power		Energy		Recovery
	Technical			Stormwater		Thermal		Restoration
	Managerial					Hydro power		Renascence
	Funding					Biosolids		
	Capital					Landscape		
	Operational					Recreation		
	Geography					Ecological		
	Location					Underground		
	Distance					Surface		
	Boundary					Environmental		
	Time							
	Instance							
	Span/Period							
	Limit							

Illustrative pathways of water reuse – total = 113,400,000:

- Federal policy-legislative driver of centralized traditional surface water reclamation for potable direct use by citizens for public health security.
- State technology-processing norm for onsite alternative-process water-agriculture-irrigation recycling for non-potable landscape use by industry for water security.
- Tribal geography-location barrier for distributed stormwater residue for ecological environmental use by nature for ecosystem resilience.

Figure 1. Ontology of water reuse.

2.1.2. Process of Water Reuse

The stages of the water reuse process are derived from the common body of knowledge and extended to include rejection and residue as the first and the last stages. Reclamation, recycling, and reuse are commonly used in many definitions [21,24–27]. Rejection [28] is not commonly used but is included in the taxonomy as a logical first stage. Similarly, residue is the logical last stage of the process—recognizing that some water may not be reused by a stakeholder. Procházková et al. [29] (p. 1) state the importance of managing the residue: “. . . water should be reused in a responsible and sustainable manner because if the liquid residue after water reuse has not been appropriately treated, it may pose a risk to both human health and the environment”.

The stages of the water reuse process are generally sequential. While ideally one may want to have both rejection and residue be zero, and maximize reclamation, recycling, and reuse, that is unlikely.

2.1.3. End Use of Water

The taxonomy of uses of water is based on the classification by Hayek et al. [20] (p. xii). We have retained their major potable and non-potable categories, but have reorganized the subcategories based on the literature [21,24–27,30]. In addition, we have added a third major category of end use—Ecological, with three subcategories of underground, surface, and environmental. The potable and non-potable water that is not reused will in a sense be ‘used’ by the ecology. The completion of this reuse sequence will be an important segment of the circular economy of water reuse [24,31–34]. While the time horizons of potable and non-potable reuses are short, that of ecological reuse is long. The desirable and undesirable

effects of ecological reuse can emerge and be propagated over a long period of time and large distances.

2.1.4. Water Reuse Definition

This ontological definition of water reuse encapsulates $14 \times 5 \times 20 = 1400$ potential combinations of source–process–end use. It includes, for example, the following: (a) traditional surface water reclamation for direct potable use, (b) alternative process water agriculture–irrigation recycling for non-potable landscape use, and (c) stormwater residue for ecological environmental use. It encapsulates and extends the present definitions of water reuse. Only a subset of the 1400 potential combinations may be instantiated at one place at a time; many may not be instantiable.

2.2. Stakeholders

There are many stakeholders in water reuse, each with their own perspectives, motivations, and interests [1,20,35,36]. We have broadly categorized them as belonging to the government, utilities, industry, citizenry, and nature (at large). They are listed in the corresponding column (Figure 1—Stakeholder). The list can be lengthened, shortened, aggregated, and disaggregated.

Thus, the three types of water reuse illustrated earlier may be combined with the types of stakeholders as follows: (a) traditional surface water reclamation for direct potable use by citizens, (b) alternative process water agriculture–irrigation recycling for non-potable landscape use by industry, and (c) stormwater residue for ecological environmental use by nature. In combination with the five types of stakeholders, there are $1400 \times 5 = 7000$ pathways.

2.3. Outcome

The desired outcomes of water reuse are listed in the last column (Figure 1—Outcome). They are public health security, water security, and ecosystem resilience.

Globally, all water is essentially reused water [1], and water is essential for the health and wellbeing of the public. All reuses of water must assure the public's health security. This includes prevention, detection, reporting, responding, managing systems, managing norms, and managing risks of factors that may affect public health security [37–39].

Changes in global climate, demographics, agriculture, and industry are increasing the role of water reuse in assuring water security. An outcome of water reuse is to improve the availability, accessibility, quality, equity, and sustainability of water locally, regionally, nationally, and globally [40–42].

The ecosystem is an essential part of all water reuse—it is the ultimate source and sink of water. The resilience of the ecosystem is critical to the sustainability of water reuse. The ecosystem is the end user of water rejected for reuse and water that is the residue of reuse. The ecosystem must be resilient to changes due to water reuse for the latter to be sustainable. Ecosystem resilience denotes the capability to recognize changes, resist dysfunctional ones, respond to them, recover from them, restore the ecosystem, and potentially revive the same [43,44].

Combining the outcomes with the three illustrative pathways, we have the following: (a) traditional surface water reclamation for direct potable use by citizens for public health security risk management, (b) alternative process water agriculture–irrigation recycling for non-potable landscape use by industry for water security equity, and (c) stormwater residue for ecological environmental use by nature for ecosystem resilience restoration. In combination with the 18 outcomes, there are $1400 \times 5 \times 18 = 126,000$ pathways.

2.4. Scale

The scale of water reuse may be one or a combination of three: centralized, distributed, and onsite (Figure 1—Scale) [20]. Generally, centralized systems cover a large geographical area, have multiple sources, cater to many end users, and handle large volumes of water

for reuse. Distributed systems cover a smaller geographical area, cater to a few sources and end users, and handle moderate volumes of water for reuse. Onsite systems are designed for individual sources and users and handle a small volume for reuse. The complexity of the reuse process will likely be proportional to its scale; the number of stakeholders will also be similarly proportional.

Thus, the three illustrative pathways can be (a) centralized traditional surface water reclamation for direct potable use by citizens for public health security, (b) onsite alternative process water agriculture–irrigation recycling for non-potable landscape use by industry for water security, and (c) distributed stormwater residue for ecological environmental use by nature for ecosystem resilience. In combination with the three scales of operation, there are $1400 \times 5 \times 18 \times 3 = 378,000$ pathways.

2.5. Action

The actions for water reuse (Figure 1—Action) will be determined by the agents (Figure 1—Agent) and the impetus (Figure 1—Impetus) they provide. Many agents may provide the impetus; and these agents may drive it, normalize it, or be barriers to it. We shall describe the two in slightly greater detail next.

2.5.1. Agent

Many categories of agents, each with multiple subcategories, may provide the impetus for water reuse. The ontology lists policies, technology, communication/outreach, workforce, funding, geography, and time. These categories and subcategories are simply a reorganization and relabeling of the terminology in the vast body of literature on water reuse. The policy subcategories are based on Lascoumes et al. [45], the technology subcategories are derived from the literature and correspond to the stages of processing water for reuse, the communication/outreach subcategories denote the two broad methods practiced today, the workforce and funding subcategories are derived from the literature and correspond to the divisions in practice, and the geography and time categories are logical parameters that affect water reuse.

2.5.2. Impetus

The agents may drive water reuse, normalize it, or be barriers to it. The categories of drivers and barriers are widely used in the literature [46], that of norms is not. Yet, norms are implicit in the research and are essential for effective water reuse. In a sense, the ultimate objective is to normalize water reuse. Norms are also necessary, as reference levels, to manage the drivers and barriers through feedback and learning [10].

2.5.3. Summary of Action

The ontology encapsulates $25 \times 3 = 75$ Agent–Impetus combinations. They include, for example, the following: (a) policy—legislative driver, (b) technology—processing norm, and (c) geography—location barrier. Thus, extending the earlier illustrations, one may have (a) policy—legislative driver of centralized traditional surface water reclamation for direct potable use by citizens for public health security, (b) technology—processing norm for onsite alternative process water agriculture–irrigation recycling for non-potable landscape use by industry for water security, and (c) geography—location barrier for distributed stormwater residue for ecological environmental use by nature for ecosystem resilience. In combination with the action combinations, there are $1400 \times 5 \times 18 \times 3 \times 75 = 28,350,000$ pathways.

2.6. Scope

Last, the scope of the water reuse problem may vary (Figure 1—Scope). It ranges from the international to the local, and includes federal, state, tribal, and local. Scope defines the boundary of a water reuse project; yet, given the property of water to freely move across

geographical boundaries, the definition of scope becomes fuzzy. A state water reuse project may have to necessarily consider federal, state, and local policies in implementation.

Thus, in combination with the scope one may envision the following (Figure 1): (a) federal policy—legislative driver of centralized traditional surface water reclamation for direct potable use by citizens for public health security, (b) state technology—processing norm for onsite alternative process water agriculture–irrigation recycling for non-potable landscape use by industry for water security, and (c) tribal geography—location barrier for distributed stormwater residue for ecological environmental use by nature for ecosystem resilience. In combination with scope, there are $1400 \times 5 \times 18 \times 3 \times 75 \times 4 = 113,400,000$ pathways for water reuse encapsulated in the ontology.

2.7. Summary of Ontology of Strategy for Water Reuse

The ontology of water reuse is a theory of a complex problem [10]. It is a clear, concise, and comprehensive organization of 122 key terms (words/phrases, excluding the column labels and connectors) and their taxonomies that define water reuse. It encapsulates the key terminology and taxonomies [4] of the domain grounded in the global research literature on the subject. It organizes a very large number of all possible nine-word/phrase combinations (${}_{122}C_9 = (122!/113! \times 9! = 1.22 \times 10^{13})$) corresponding to the nine columns and sub-columns of the ontology) into 113,400,000 semantically and practically meaningful pathways of water reuse. It visualizes the complexity of the problem in structured, natural English. While, at first glance, it may appear to be abstract and impractical, it is in fact concrete and practical—an illustration of the aphorism that there is nothing as practical as a good theory [47]. It can be used to describe the many pathways of water reuse in a context, explain their antecedents and consequences, predict the outcomes based on past research and practice, and control the trajectory through feedback and learning.

The ontology, by necessity, is complex—it is an isomorphic representation of a complex problem. It is also modular. Elements and pathways applicable to a context may be extracted and used without diminishing the effectiveness, thus reducing the complexity, yet addressing the problem systemically and systematically. Thus, although the scope of the present ontology is global, it can be reduced and simplified to apply locally without a loss of perspective and reducing the unintended consequences of a narrow perspective. The ontology can effectively capture wide-ranging water reuse initiatives at the international or regional levels as well as the local or municipal levels. For example, the unified water reuse strategy by the Gulf Cooperation Council (GCC) countries [48] involves both regional and municipal considerations of water reuse, which can be succinctly captured by the ontology. Similarly, the ontology can capture water reuse policies or initiatives by various countries around the world [49–55].

We have used the metaphor of Google Map to characterize the ontology. Like a Google Map when studied closely, the ontology presents a very large number of pathways to reuse water. One must select the preferred pathways based on the stakeholders' desired criteria—such selection is automated in Google Maps to reduce the complexity of choice. Thus, it will help locate one's state of water reuse on the map, define the desired state, determine the gap, and design pathways to bridge the gap.

A coordinated national research strategy for water reuse must help discover the following pathways for all stakeholders:

- Effective pathways across the ontology and how to reinforce them;
- Ineffective pathways across the ontology and how to redirect them;
- Innovative pathways across the ontology and experiment with them;
- Infeasible pathways across the ontology to avoid them.

In the following discussion, we describe a process of developing a national research strategy for water reuse using the ontology.

3. Discussion—National Research Strategy for Water Reuse

Stakeholders, by definition, have a stake in defining and addressing the problem of water reuse locally, tribally, regionally, nationally, and globally. Stakeholders may be government bureaucrats, water utility managers, industry users, citizen activists and users, and nature, which provides, sustains, and consumes water. Stakeholders are also likely (and understandably so) to be guided by their self-interest and thus to take a narrow, segmented approach to the problem. There is an inherent incentive to replay the story of the blind men and the elephant. Without a ‘Google Map’ of the problem, the stakeholders are likely to continue to talk past each other, become entrenched in their positions, reinforce past biases, not see the ‘big picture’, and see alternative win–win pathways. The ontology can make the ‘elephant’ visible. Studies on national healthcare policies [12–16], higher education policies [56], transboundary sharing of river water [11], and clean air policies [57] using ontologies provide evidence of the siloed, selective, sparse, segmented, and non-systemic. They are siloed in that the emphases on the columns are severely unbalanced, selective in their choice of elements addressed, sparse in the overall coverage of elements and the attendant pathways, segmented attention to pathways, and because of all the above, inattentive to addressing the problem systemically.

The federal government or a designated national research body of a country must play a central role in developing a national research strategy for water reuse, translating research into policies, translating policies into practice, and modifying the research strategy based on the feedback from the implementation of the policies and practices. Given the complexity of the challenge, an ad hoc strategy, like those that have been pursued to date, will be inadequate. These recommendations are based on the policy briefs developed for the G20 Summit in India in 2023 [58,59].

At present, there does not appear to be any national framework or concerted effort to address the challenge of water reuse and provide a roadmap. Each national body’s agenda must inform and be informed by the constituent state/province, tribal, and local agendas, those of other countries (especially the neighbors), and those of the United Nations (UN) and its agencies, the World Health Organization (WHO), and similar bodies.

The ontology of the strategy for water reuse or a similar one must be adopted as a framework for every country and its constituent entities. Within the framework, each entity must choose its pathways based on its local requirements, priorities, and resources. The adoption of a common framework will help formalize and transfer knowledge about and feedback and learnings from the implementation within a country and to other countries. Such an approach will help move the cycle of generating and applying knowledge on the challenge from a selective, segmented, and siloed effort to a synoptic, systemic, and systematic one.

The framework must be used to periodically map the state-of-the-art, state-of-the-need, and state-of-the-practice of water reuse. Analyzing the gaps between the three states must guide the translation of research into policy into practice and then back into research for feedback and learning to achieve the sustainable development goals’ vision. As such, national committees must help the member countries collaborate, coordinate their policies, and communicate their learning.

Each national body must form a national committee and encourage the creation of regional and local groups for water reuse. These committees must adapt and adopt the ontology as a common framework and pursue a systemic approach that harnesses the resources and unleashes the forces necessary for water reuse. These committees must be responsible and accountable for the outcomes.

A recommended agenda for national bodies is as follows:

- Finalize the ontology in consultation with stakeholders and researchers through extensive meetings;
- Finalize the corpus of the national and global research literature on water reuse;
- Map the documents onto the ontology to determine the following:

- a. Elements of the ontology that have been heavily addressed (bright spots), less addressed (light spots), and not addressed (blind/blank spots) in the corpus;
 - b. The primary, secondary, tertiary, quaternary, and quinary themes in the corpus;
 - c. These maps will highlight the gaps within the corpus.
- Solicit feedback from stakeholders and researchers based on the ontology and the maps derived from the corpuses;
 - The feedback should help prioritize the pathways to be reinforced, redirected, experimented, and avoided;
 - The priority of pathways to be reinforced, redirected, experimented, and avoided shall form the basis of project ideas and research roadmaps;
 - Develop a final roadmap anchored on the ontology, the mapping of the corpus, and the feedback from the stakeholders and researchers;
 - Like a Google Map, the roadmap shall highlight the key pathways and their priorities;
 - The roadmap shall be disseminated via the document, presentations, webinars, and roundtables;
 - The ontology and the associated maps will be the basis for scientifically (a) describing the pathways to water reuse, (b) explaining their logic, (c) predicting the outcomes of choosing different pathways, and (d) controlling the outcomes through continuous feedback and learning.

Technology, both modern and traditional, should be a key focus of the national research strategy for water reuse. Water use and reuse must be managed minute by minute, mile by mile, through deluge and drought. Modern information technology like sensors, unmanned aerial vehicles (UAVs), internet of things (IoT), robots, and Geographic Information Systems (GIS) provide powerful tools to micro-manage water reuse spatially and temporally. They can provide the data, information, interpretation, and knowledge in real time to manage water reuse through feedback, control, adaptation, learning, and redirection. They must be deployed extensively as part of the national research strategy for water reuse.

At the same time, nature is one of the biggest stakeholders in water reuse. Many traditional, historical nature-based technologies for water reuse are being rediscovered and redeployed [60–62]. These technologies rely less on modern discoveries and more on harnessing the natural properties of the land, flora, and fauna. They are dependent on biochemical and physical feedback and control mechanisms. Many incorporate learning and adaptation over many past generations. These technologies too should be an integral part of the national strategy for water reuse.

4. Conclusions

The complex challenge of a national water reuse strategy cannot be simply the sum of many local, incremental, and ad hoc strategies. A synoptic view of the problem, as provided by the ontology, is necessary to address it systematically and systemically. The fragmentation of the formulations and segmentation of the solutions can diminish the intended, functional consequences, and enhance the unintended, dysfunctional consequences. They can lead to biases and blind spots in addressing the problem. A way to optimize the effort for water reuse is as follows: (a) have a roadmap like the ontology of water reuse strategies that has been proposed; (b) institute a process for continuous feedback and learning with stakeholders; (c) institute a process for continuous feedback and learning between research, policies, and practices; and (d) adapt the roadmap as new knowledge is generated. One could, using this approach, bring about a revolutionary change in the strategic management [9] of water reuse.

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