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# Institutional barriers to on-site alternative water systems – A conceptual framework and systematic analysis of literature

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ABSTRACT. Scientists are increasingly exploring on-site water systems to supplement conventional centralized water and wastewater infrastructure. While major technological advancements have been achieved, we still lack a systematic view on the non-technical, or institutional, elements that constitute important barriers to the uptake of on-site urban water management systems. This paper presents a conceptual framework distinguishing between institutional barriers in six key dimensions: *Equity*, *Knowledge and Capabilities*, *Financial Investment*, *Legal and Regulatory Frameworks*, *Legitimacy,* and *Market Structures*. The analysis of existing literature covering these barriers is translated into a typology of the socio-technical complexity of different types of alternative water systems (e.g. non-potable reuse, rainwater systems, nutrient recovery). Findings show that socio-technical complexity increases with the pollution load in the source water, correlating to potential health risk, and the number of sectors involved in the value chain of an alternative water system. For example, greywater reuse for toilet flushing might have systematically less complex institutional barriers than source separation for agricultural reuse. This study provides practitioners with easily accessible means of understanding non-technical barriers for various types of on-site reuse systems and provides researchers with a conceptual framework for capturing socio-technical complexity in the adoption of alternative water systems.

## SYNOPSIS

This study compiles institutional barriers for urban, on-site alternative water systems, improving implementation of new water and wastewater infrastructure.

## INTRODUCTION

Urban water management (UWM) stands at an important crossroads. Urbanization, climate change, and depletion of natural resources increasingly challenge the conventional paradigm of centralized water supply, treatment, and reuse[1–3]. There is growing evidence that addressing key challenges for UWM requires a fundamentally new paradigm that embraces a broad variety of alternative, on-site water systems that are implemented in parallel with or as a substitute to expansive sewer-based systems[2,3,3,4]. This study utilizes the term *on-site* defined by Sharvelle et al. (2017) as systems "in which local sources of water (e.g., roof runoff, stormwater, graywater, and wastewater) are collected, treated, and reused at the building, neighborhood, and/or district scale, generally at a location near the point of generation of the source of water"[5]. Yet, due to a lock-in of conventional technology and centralized infrastructures, various experiments with on-site recycling technologies have been initiated, but larger uptake of the concept in urban areas is relatively slow; this is often associated with a broader 'innovation deficit' in the water sector[6]. The discussion on an imminent transition to on-site systems in UWM is still largely technocentric, emphasizing technology development as the main strategy to remove barriers to diffusion. This paper contends that there is a need to more systematically explore the manifold *institutional barriers*, which hinder the uptake of new technologies and system designs. Institutions provide the "rules of the game", such as regulative, normative, and cultural-cognitive elements[7]. For example, cognitive stigmas like the 'yuck factor' hinder a quick diffusion of potable water recycling technologies, thus requiring targeted efforts to shift cultural interpretation of wastewater as a resource[8]. In most cases, technological and institutional factors closely influence each other in so-called socio-technical systems[9]. In this paper, we thus seek to identify patterns in the amount and multi-dimensionality of interconnected institutional and technical barriers, which we define as the *socio-technical complexity* of an alternative water system.

A broad body of literature exists addressing this topic, however it is scattered across social science and engineering literature. Existing literature largely focuses on broad conceptual discussions of an imminent transition in UWM[6,10], individual case studies of on-site reuse systems[11,12], or feasibility and acceptance studies[13,14]. This paper capitalizes on the broad knowledge distributed throughout this literature, systematizing the state of the art of conceptual and empirical knowledge into a conceptual framework of the key institutional barriers for the diffusion of on-site UWM systems in urban areas.

Academic literature is systematically analyzed to identify the types of institutional barriers inhibiting the uptake of on-site UWM technologies in urban areas, to assess how these barriers differ across technology configurations, and to derive implications on how 'socio-technical complexity' differs between different water reuse approaches. This study found that to scale adoption of on-site reuse systems, there is a need to address both the specific institutional barriers of different alternative water systems and develop long-term policy strategies for addressing complex issues spanning various dimensions of our framework.

## POINT OF DEPARTURE

### Institutional lock-in and complexity in the UWM sector

UWM is repeatedly characterized as a particularly rigid and inert sector, which is locked-in to one dominant technical solution - expansive piping networks and centralized treatment[15–17]. The reasons for this lock-in range from sunk costs and network externalities in centralized piping infrastructure[18], to its close connection with public health issues[15], and dependence on government interventions and technology standards[19]. In addition to these rather technical barriers to innovation, there are also many barriers that stem from social or institutional structures[15]. One way to conceptualize this path-dependency is to conceive of UWM as a socio-technical system with a deeply institutionalized, dominant regime[17,20]. Centralized infrastructure has evolved into the dominant design in the water and wastewater sector over the past hundred years and in the process has developed economies of scale, supportive actor structures, and deeply routinized ways of doing things[21]. Diffusing a disruptive innovation like on-site water reuse deeply challenges many of these taken-for-granted structures and requires a 'regime shift', in which key technologies, actor networks and institutions are re-aligned or newly created[16,20].

In social theory, institutions are not defined as organizations, but as the legal, cultural, and normative "rules of the game" that shape people's and organization's actions, thus constituting various opportunities for and barriers to innovation[7]. In UWM, relevant institutions range from "*formal regulations, such as laws and water quality standards, to more intangible rules, such as cultural norms on how to properly use a toilet, or cognitive frames, such as the political and public perception of different technologies*"[16]. In the same way these institutional elements have been developed over time for centralized infrastructure, innovative technologies (e.g. on-site water reuse) that detract from this dominant regime also require new or adapted institutional support structures, containing similar types of institutional elements (e.g. norms, laws, financing, cultural preferences) (ibid.).

The introduction of on-site reuse systems in cities raises the question of compatibility and interdependence between the support structures of the old 'regime' and newly emerging 'niche' solutions [22–24]. Each of these institutional support structures align with unique ideologies that have certain demands; for example, conventional utilities prioritize security of service provision through large infrastructure projects, whereas practitioners championing on-site reuse prioritize fit-for-purpose technological configurations for context-specific provision of water and wastewater services[17]. This example and existing literature show that a shift to on-site technologies will inevitably induce socio-technical complexity in the UWM sector, but we lack a clear understanding of how this complexity will vary between the manifold technological configurations that are currently proposed for novel on-site UWM solutions. This is a relevant gap, since recent proposals for on-site UWM range from installing rain gardens and 'water-sensitive urban designs'[25,26] to equipping new residential, commercial, and public buildings with on-site non-potable reuse (NPR) systems (e.g., San Francisco[27], Beijing[28]), to introducing recovery of nutrients from composting toilets in new city districts (e.g. Sweden[29], Finland[30]). This paper thus aims at systematizing the existing evidence on what sort of institutional barriers and socio-technical complexity can be expected for the diffusion of these different technological approaches.

## Toward a conceptual framework for institutional factors that influence the diffusion of on-site water reuse in cities

A dichotomy presently exists in literature where studies focus on one of two extremes: specific case studies discussing the barriers associated with implementing a particular type of on-site technology and broader conceptual discussions of barriers in the UWM field as a whole, without accounting for diversity of challenges across these alternative systems. A conceptual framework is necessary to provide comprehensive definitions of the key dimensions within an institutional support structure that influence the wider diffusion of on-site UWM solutions.

Especially with regards to the latter point, several authors have recently provided conceptual frameworks on the barriers and opportunities for transitions and deep institutional change in UWM[6,18,31]. These are efforts to develop a more explicit 'urban water transitions framework', based largely on the experience of Australian and, to a lesser degree, American and European cities[4,25,32–34]. These contributions have been beneficial in conceptualizing the complex management and governance issues around a transition in the urban water sector at large[4,33–36]. Yet, they mostly refrain from specifying key institutional barriers for urban water reuse in a heuristic that distinguishes between different types of on-site technologies.

To address this gap, we propose a conceptual framework, which targets the middle ground between micro-level case studies and macro-level conceptualizations. More specifically, our framework is rooted in the work on technological innovation systems (TIS)[37] and on 'enabling environments' for UWM innovation[2,38–41]. The TIS approach has specified several lists of 'functions' or 'activities' that are seen as necessary conditions for technology diffusion[37,42]. We instead focus more generically on institutional 'dimensions' in our conceptual framework (table 1). Both UWM innovation and TIS literature provide a structured view on the key dimensions that are crucial for diffusing transformative innovation in UWM. That is, if one dimension (e.g., financial investment or legitimacy) is missing, the new technology will run into outright opposition or skepticism with key stakeholders, creating major barriers to diffusion.

TIS literature systematically differentiates key dimensions, in which institutional change processes go hand in hand with technological innovation[1,37]. While initial TIS studies focused on seven system 'functions', more recent literature distinguishes between four key 'system resources' needed to jointly mobilize technology diffusion: knowledge and capabilities, (niche) markets, financial investment, and legitimacy[37,42,43]. While these system resources are backed by innovation studies and expansive empirical evidence from emerging clean-tech sectors (e.g. renewable energy, electric mobility, waste management), they miss certain elements that are of key importance in supporting disruptive innovation specifically in the UWM sector. We thus add two additional dimensions from the literature on innovation in UWM, specifically legal and regulatory mechanisms, and equity[38,40,41,44]. The exact definition of each dimension and examples from UWM are provided in table 1 and the two additional dimensions (*Equity* and *Legal and Regulatory Frameworks*) are explained further below.

In the case of UWM, legal and regulatory frameworks such as water laws, public health standards, technology standards or building codes play a crucially important role in defining what kind of innovative technology is conceivable or not[19,45]. Whether and how skillfully the proponents of on-site UWM systems are adapting existing regulative frameworks is a key determinant of innovation success and the wider societal legitimation of the new technology[43]. Since the TIS framework does not list this dimension separately, we here follow the literature on innovation in UWM in listing it as its own dimension.

A second dimension that is currently absent in TIS literature is equity. Equity comprises multiple components, including the distribution of access (both the quantity and quality thereof) to basic water and wastewater services in a given community, affordability, reliability of distribution, as well as participation and representation in decision-making and the implementation of service provision[46,47]. Equity issues have thus far been largely downplayed in the literature, even though centralized systems (e.g. in developing and emerging economies) often provide socially segregated service levels[48,49]. Since on-site UWM is implemented in a spatially much more selective manner, equity implications almost automatically move center stage[50]. Equity implications require further attention to minimize future unintended consequences. Additionally, consideration of equity may serve as a justification for alternative water systems as an opportunity to address existing inequity in centralized networks.

**Table 1.** Definitions and examples for the key dimensions for UWM innovation, drawn from literature on enabling environments for UWM innovation[38,39,41] and technological innovation systems (TIS)[37,42].

| Dimension | Definition | Operationalization for UWM |
|---|---|---|

| | | |
|---|---|---|
| *Equity* | Structures that guarantee the reliable and affordable provision of an acceptable minimum quality and quantity of water service to all end-users. These same structures also allow for broad and inclusive representation and participation of affected social groups in all stages of the decision-making and planning processes[46,47]. | – Affordability of systems operation and maintenance<br>– Public participation programs in planning / siting decisions of new treatment plants |
| *Financial Investment* | Structures that mobilize and allocate financial investment for the new technology. This includes bank loans, equity/angel investments or (government) subsidies allocated over the whole lifetime of a project, including operation and maintenance. | – Grant programs that offset initial costs for installation<br>– Water and wastewater pricing schemes<br>– Investment incentives for private real estate companies, firms, etc. |
| *Knowledge & Capabilities* | Structures enabling the creation and diffusion of new technological knowledge as well as structures that increase the capacity of practitioners (e.g. workforce development) to operate and manage innovative technology. | – Research and development programs<br>– Training modules for designers, equipment suppliers, engineers operators, permitting staff<br>– Technology workshops and conferences |
| *Legal & Regulatory Framework* | Regulation used for structuring the design, installation, and operation/maintenance of new technologies. This also includes legally binding performance criteria, testing and monitoring procedures, and equipment standards. | – Laws or programs requiring the installation of on-site reuse technology<br>– Permitting pathways, enforcement requirements for on-site reuse systems |
| *Legitimacy* | The "generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions."[51] Legitimation activities can explain benefits and align the innovation with the widely held norms, beliefs, and ways of doing things in a given context[8]. | – Education / outreach campaigns to change user preferences<br>– Quality certification (e.g. through ISO, UL, etc.)<br>– Safety protocols, consistent quality monitoring procedures |
| *Market Structures* | Development of a market for the new technology, e.g. through demonstration and lighthouse projects, the creation of a protected market segment (e.g. subsidies), codification of the demand, exchange, and supplier structures around a new technology. | – Creation of new business models with high return on investment<br>– Vetting equipment suppliers<br>– Achieving economies of scale in production / service |

It is important to note that the six dimensions of our conceptual framework are mutually interdependent as foundational components to the governance structure that incentivize, regulate and monitor a new technology configuration, and thus are jointly capable of catalyzing or inhibiting the uptake of an innovation. Coordination across them may be achieved by intermediary actors (e.g. industry associations, universities, NGOS, etc.) or more generally through a well-defined governance structure that clarifies the roles and responsibilities of all involved stakeholder groups[52–54]. This relationship between the dimensions and the governance structure is provided in appendix A. The success or failure of innovative on-site technology is then contingent on each dimension maturing and mutually aligning with the others. Simply put, if barriers in one dimension persist, or misalignment exists across multiple dimensions, then the whole innovation system may fail, inhibiting uptake. For the purpose of this paper, we focus on the dimensions presented in Table 1 as ways to aggregate the institutional barriers observed in peer-reviewed literature for urban, on-site alternative water systems.

One example might be that a sophisticated technological solution does not attract sufficient financial investment, inhibiting the formation of economies of scale, which keeps its price prohibitively high even in niche markets, which ultimately undermines the technologies' wider societal legitimacy. Developing an improved governance arrangement, for example in which private real estate developers and the local utility share the costs for installation and maintenance of on-site system based on clearly defined contractual terms, may help to overcome both the deficit in one dimension and its coordination with other related parts of the system.

With this conceptual framework, we present a systematic overview of peer-reviewed, academic literature to observe whether we can identify certain combinations or patterns of institutional barriers that are characteristic for different types of on-site reuse technologies. Additionally, these combinations of barriers will be discussed to identify any patterns that can delineate the degree of socio-technical complexity that might exist for different types of alternative water system.

## METHODS AND MATERIALS

### **Differentiating various on-site alternative water systems**

As mentioned above, the spectrum of technological solutions that are proposed for on-site UWM is remarkably broad. To be able to discuss these different technologies in a structured way, a typology of different on-site UWM solutions is needed. We systematize alternative water systems by their source and recovery purpose (fig. 1), using definitions for the various sources provided in Sharvelle et al. (2017). The authors acknowledge that many definitions exist for the various sources of recovery. In this paper, we root our definitions in Larsen et al. (2016), fig.3. Stormwater represents "*precipitation runoff from rain or snowmelt events that flows over land and/or impervious surfaces*"[5]. Rainwater, in turn, often describes rainfall captured prior to runoff, possibly requiring less treatment prior to end use; for the purpose of this study, stormwater and rainwater are combined into one source category. Greywater is "*wastewater collected from non-blackwater sources, such as bathroom sinks, showers, bathtubs, clothes washers, and laundry sinks*"[5]. Blackwater is defined as "*wastewater originating from toilets and/or kitchen sources (i.e., kitchen sinks and dishwashers)*"[5]. Finally, wastewater is defined as a combination of both blackwater and greywater sources. Recovery purposes include non-potable reuse (NPR), potable reuse, and agriculture; industry applications have been excluded from this study.

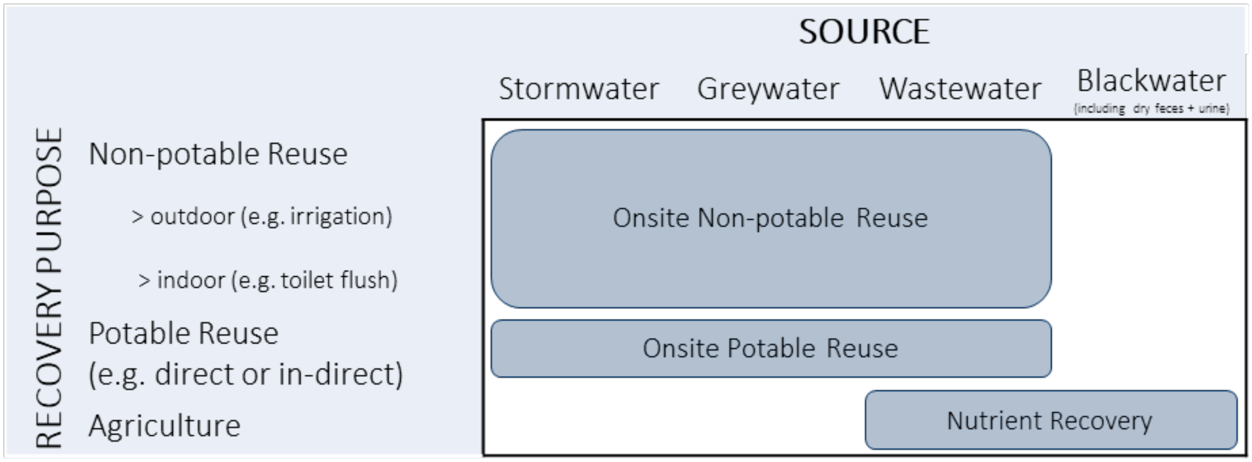


**Figure 1.** Typology for alternative water systems organized by source and recovery purpose.

## Data collection and analysis

A systematic analysis of literature was undertaken using the guidelines for the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA)[55]. First, an initial list of search terms was developed based on the scope of the project (see appendix B); for example, types of water streams (e.g. greywater, blackwater, stormwater) and types of on-site systems (e.g. decentralized, non-grid). These key search terms were applied to both the Web of Science and SCOPUS databases using Boolean connectors (see appendix C, D for an overview of the process). The goal in the retrieval process was to identify journal articles that focus on real-world applications of on-site water reuse technologies in urban contexts, and which contain a dedicated discussions of institutional barriers (see table 2). The initial results were narrowed down by removing subject area (e.g. dentistry, solid waste management, etc.) or search terms that were pointing to unrelated articles (e.g. 'pig,' 'vineyard,' and others, see appendix D for full list). After this initial filtering process, articles were examined in iterative steps by title and abstract. The eligibility criteria was based on articles' methodology, topical focus, and context. For example, articles that were based in rural settings or looked at centralized systems rather than on-site systems were not considered (see appendix C, D). A summary of the eligibility criteria used to narrow the analysis to the final group of included articles is shown in table 2.

After this iterative process, results from both databases were combined and duplicates were removed from the list (621 articles). Articles were again reviewed to confirm that eligibility criteria were met (table 2) (350 articles). This intermediate group of articles was documented by date, location, economic status (as outlined by UN DESA[56]), source, and recovery purpose. The final iteration of the data analyzed the body of the remaining journal articles to identify whether the study explicitly mentioned and discussed institutional barriers in their work. This resulted in 39 articles, which were qualitatively coded and analyzed in-depth through thematic coding with NVivo software (version 12) in two steps: 1) identifying institutional barriers, and 2) organizing these barriers using the conceptual framework in table 1. The identified institutional barriers were coded deductively to one of the dimensions of the conceptual framework, based on definitions and operationalizations from table 1: *Equity, Financial Investment, Knowledge and Capabilities, Legal and Regulatory Frameworks, Legitimacy, and Market Structure.* These results were further assessed for barriers in which dimensions were most prevalent for different types of alternative water systems.

**Table 2.** Eligibility criteria used for the final list of articles included in this analysis. Final list of articles shown in appendix F.

| **Eligibility criteria** | **Description** |
|---|---|
| *1. Peer-reviewed literature* | Articles that have gone through a peer-review process. This excludes grey literature, but examples of relevant reports have been included in the broader discussion. |
| *2. Alternative water system* | Discussion of an alternative water system, as shown in fig. 1. |

| | |
|---|---|
| *3. Urban contexts* | Studies focused in urban or peri-urban contexts. Some studies included a cross-comparison between rural and urban contexts; these were initially included, provided that the other eligibility requirements were met. |
| *4. Decentralized scale* | Non-centralized scales were considered. Some studies include cross-comparison between centralized and decentralized scales; these were initially included, provided that the other eligibility requirements were met. |
| *5. Based on implementation of a project* | The goal of this project is to capture barriers encountered during the real world implementation of alternative water systems. As such, feasibility/prospective studies and modelling applications were not included. |
| *6. Discusses non-technical challenges* | Papers were included if they discuss institutional barriers that could fall under one of the six dimensions in table 1. |
| *Exceptions: there are a handful of synthesis papers giving a high-level discussion of the state-of-the-art for alternative water systems. These were incorporated into the final list of articles because of their extensive references to relevant literature.* | |

The literature can be subject to publication bias, or the possibility that some relevant contributions were not published due to unclear methodology, generalizability or the lack of a 'success story'[57,58]. For example, some studies in our dataset specifically focus only on the regulatory barriers for a certain alternative water system[59,60], this emphasizes certain types of barriers over others. To account for these potential biases, we note the predominant barriers per publication, but also discuss the most salient barrier constellations in a more qualitative analysis. Future work could complement this study with questionnaire-based validation of the suggested relationship between barriers and socio-technical complexity in on-site UWM systems (fig. 2).

## RESULTS

In this section, we first look at the global trends visible from the peer-reviewed literature at the level of the intermediate set of 350 articles. The remaining sections take a closer look at specific trends in the type of institutional barriers encountered for the 39 articles that were qualitatively coded.

### Broader literature in alternative urban water systems (350 articles)

Results from intermediate aggregation are shown in table 3. About two thirds of the relevant literature represents urban areas of developed economies (mostly in Australia, the USA, Spain, Germany, the UK, and Sweden), while one third of the reported systems are located in urban centers of developing and emerging economies (mostly China, India, and South Africa); 75 countries are represented in total for these intermediate results (see: appendix E). Our results further reveal that, across all socio-economic contexts, most academic interest revolves around stormwater for NPR; greywater and wastewater for NPR; as well as wastewater and blackwater for agricultural reuse purposes. Studies in emerging economies seem to explore greywater reuse for NPR more than in developed economies. Yet, apart from this distinction, the distribution of studies looks very similar across socio-economic contexts. In the remainder of the study, we thus largely abstract from socio-economic status and discuss institutional barriers at a generic, global level (shown in table 3).

While these studies contribute to the larger discussion on urban water management, this study is focused on a specific subset with the following requirements: urban, on-site, alternative water systems (with a source being recovered for a purpose), either summarizing the general state-of-the-art or referencing a specific implementation project, and discussing non-technical barriers of the project (table 2).

**Table 3.** Number of articles per type of socio-economic context (developed, developing economies, based on definitions provided by UN DESA[56]) and alternative water system (e.g. water source and recovery purpose). Note: some articles discussed multiple types of contexts and alternative water systems, which is reflected by the presence of more than 350 articles across the charts.

| Developed Countries | | SOURCE | | | |
|---|---|---|---|---|---|
| | | Stormwater | Greywater | Wastewater | Blackwater (including dry feces + urine) |
| RECOVERY PURPOSE | Non-potable Reuse | 71 | 71 | 46 | 6 |
| | > outdoor (e.g. irrigation) | 17 | 24 | 15 | 2 |
| | > indoor (e.g. toilet flush) | 16 | 28 | 10 | 2 |
| | Potable Reuse | 6 | 2 | 4 | 0 |
| | Agriculture | 0 | 4 | 11 | 27 |

| Emerging & Developing Countries | | SOURCE | | | |
|---|---|---|---|---|---|
| | | Stormwater | Greywater | Wastewater | Blackwater (including dry feces + urine) |
| RECOVERY PURPOSE | Non-potable Reuse | 16 | 52 | 24 | 2 |
| | > outdoor (e.g. irrigation) | 6 | 31 | 14 | 0 |
| | > indoor (e.g. toilet flush) | 6 | 28 | 6 | 2 |
| | Potable Reuse | 2 | 0 | 0 | 0 |
| | Agriculture | 0 | 1 | 7 | 20 |

**Barriers for specific types of alternative water systems (39 articles)**

Thirty-nine articles explicitly discuss institutional barriers for on-site UWM systems. In general, barriers in all six dimensions (table 1) were mentioned for the various alternative water system configurations (see subsequent sections), but barriers in certain dimensions were more prevalent for certain technologies than others. Table 3 shows the types of alternative water systems that had more than three articles included in a specific category. The percent coverage for each dimension is shown, with predominant dimensions with over 70% coverage bolded. For example, in articles that discussed alternative water systems where stormwater was recovered for NPR, barriers in all six dimensions were discussed in the articles, but only *Financial Investment* was discussed in 75% of the articles, making this a predominantly relevant dimension. Interestingly, *Equity* was not amongst the most salient barriers in any alternative water system, reflecting a broader neglect of this topic in existing literature. A few articles included in the analysis of literature noted accessibility[61], affordability[55,57,65,72], and procedural equity (e.g. decision-making processes[66,67]) as factors in the decision to adopt alternative UWM in urban areas[49]. As on-site arrangements disrupt the conventional centralized system, a multifaceted conversation around equity issues thus requires more investigation and systematic discussion in future work.

In the following sections, we discuss the barriers constellation for each of these five technological configurations (shaded sections in table 3, e.g. stormwater for non-potable reuse) in more detail.

| **Source** | Stormwater | Greywater | Wastewater | Wastewater and Blackwater (Dry feces + Urine) |
|---|---|---|---|---|
| **Recovery Purpose** | Non-potable reuse | Non-potable reuse | Non-potable reuse | Agricultural use |
| **Barriers** | *Countries: Australia, Germany, South Africa, South Korea, United States*<br><br>**Financial Investment**<br>- Installation costs<br>- Lack of financial incentives | *Countries: New Zealand, Spain, United States*<br><br>**Knowledge & Capabilities**<br>- End users need more info about how systems work<br>- Lack of education about design guidelines and standards<br>**Legal & Regulatory**<br>- Need for tailored regulations<br>- Need for standard definitions | *Countries: Australia, China, United Kingdom, United States*<br><br>**Financial Investment**<br>- High capital costs<br>- High operating costs<br>**Knowledge & Capabilities**<br>- Data is needed to create regulations<br>- More training needed for operations and maintenance<br>**Legal & Regulatory**<br>- Need for tailored regulations; enforcement<br>**Legitimacy**<br>- Perceived risk to public health | *Countries: Finland, Sweden, The Netherlands*<br><br>**Knowledge & Capabilities**<br>- Lack of research for guidance documents<br>- Information breaks in actor networks<br>**Legal & Regulatory**<br>- Strict regulation due to risk aversion<br>- Interfacing regulations from multiple industries<br>**Legitimacy**<br>- "Yuck factor"<br>- Perceived risk to public health<br>**Market Structures**<br>- Lack of strong business case<br>- Interfacing multiple industries: agriculture and wastewater infrastructure |

**Table 3.** Distribution of institutional barriers across alternative water systems (i.e. combinations of sources and recovery purposes). Percent coverage across articles included in each category is shown next to the dimension type (e.g. Financial Investment, 75%) and bolded dimensions indicate predominance, or coverage of more than 70% of articles in each category.

*Stormwater capture for non-potable reuse*

Many systems for on-site, non-potable rainwater harvesting, and stormwater collection exist, including rainwater harvesting for irrigation, toilet flushing or building cooling. Institutional barriers were observed in all six dimensions, but the largest reported challenge comes from

*Financial Investment*. The technologies are simple and well known; therefore, adoption does not run into organized opposition, but rather depends on the economic feasibility for end users[68,69].

For example, in South Africa, a combination of high initial cost for installation that was placed on families and a low tariff structure dis-incentivized adoption for on-site rainwater harvesting[64]. Similarly in South Korea, there is no legal basis for providing financial incentives[70]. *Legal and Regulatory* barriers exist in both developed and emerging economy contexts, but for a variety of reasons. For instance, in some Australian cities, the legal requirement to the uptake of on-site rainwater harvesting resulted in a lack of buy-in from end users and practitioners (*Legitimacy*), leading to failure or improper operations and maintenance[63]. In South Africa, urban rainwater systems weren't required; in fact, individuals were required to obtain permission from the local government to install any alternative water sources, hindering willingness of end users to take the additional steps necessary for installation[64]. This is similar to other contexts like Colorado, United States where for a period it was illegal to harvest rainwater on-site[71].

*Greywater recycling for non-potable reuse*

The most frequently mentioned barriers for greywater recycling for NPR are within *Legal and Regulatory Frameworks*. This was expressed through a lack of regulation associated with water quality standards, inconsistent definitions for greywater, and difficulties in adapting existing regulations that are intended for centralized systems that are not easily translated to on-site systems. In the United States, current performance-based regulation for water recycling is designed for municipal scales, creating challenges for compliance at the on-site scale[45,59,60]. In response, stakeholders have developed and are advocating for the adoption of a risk-based regulatory framework[5,72,73]. This new risk-based framework transitions from end-point assessments of water quality to a systems-based approach that assesses process performance at critical control points through log reduction targets[5]. It should be noted that previous work has shown that the scale of these systems can also affect the type of challenges faced for greywater reuse systems[60,73]. For example, greywater reuse inside one building creates fewer barriers than if it is applied at a district-level scale.

Another challenge was the discrepancy between regulations and governance arrangement; i.e. in Spain, there was initially some challenges with greywater systems because those enforcing the regulations were not involved in the development of them, causing discrepancies with implementation[74]. Another consistently mentioned barrier is *Knowledge and Capabilities*[60,74,75] and the lack of a clear governance model. On-site greywater reuse requires trained operators and external stakeholders separate from end users to perform operation and maintenance, requiring additional training and a clear organization of roles and ownership of on-site systems. A lingering question in existing literature also is the viability of the market structure for greywater systems. At the time of the studies, both New Zealand and Spain had immature markets, with few technology options and an uncertainty as to whether and how a favorable return on investment can be generated[74,75]. In contrast, the United States has the viable technology options, but currently lacks the market structure to scale up on-site greywater systems[45,60].

*Wastewater recycling for non-potable reuse*

Non-potable recycling systems that use wastewater, a combination of greywater and blackwater, generally require more complex treatment technologies than greywater systems. This need for additional treatment is also reflected in additional institutional challenges. Across the retrieved articles, barriers are consistently found in the *Financial Investment*, *Legal and Regulatory*

*Framework*, and *Legitimacy* dimensions. Since more treatment is required for wastewater than say stormwater or greywater, stakeholders and end users expressed concern about the safety of NPR systems in the United States, United Kingdom, Australia, and China[28,61,76,77]. This perception affects the legitimacy of NPR systems, leading to stricter regulations[62] to protect public safety, but also slowing the permitting process for installation. In Chinese cities, governments transposed regulations from other countries to develop their legal framework, but these regulations lacked tailoring for the local context, and issues were identified with enforcement[28,77]. Some case studies identified that regulatory frameworks were adopted due to perceived legitimacy, but the outcome demonstrated the need for each country to assess regulations and tailor for their specific context prior to adoption[77]. Multiple studies highlighted that a clear business case does not exist yet or is struggling to emerge and roles are unclear in the governance structure tasked with overseeing implementation of wastewater-based NPR systems[28,61,62,76]. Along with these challenges, financial incentives were lacking and capital costs were either unexpected or too high for projects to be economically viable in the long run, as observed in Australia, China, and the United Kingdom[28,61,76]. In a broader discussion of wastewater recycled for non-potable purposes, equity becomes an additional key consideration regarding the affordability of alternative systems for lower income communities[62].

*Blackwater or combined wastewater for agricultural reuse*

Blackwater or wastewater systems for agricultural reuse comprise nutrient recovery systems, such as source separation or composting toilets. Many systems separate blackwater from the rest of the wastewater stream to more easily recover nutrients for agricultural purposes. The main aim of these systems is thus nutrient recovery and not water recycling. The articles within this subset did not always explicitly distinguish between blackwater and wastewater as the water source;

therefore, we merge papers in both categories here. Case studies for urban nutrient recovery focus at a broad, global scale or specifically cover the Swedish experiences with urine diversion.

Barriers are consistently present in three key dimensions: *Legal and Regulatory Framework, Legitimacy* and *Market Structures*. In addition to the fear of increasing public health risks (as seen in NPR systems), legitimacy for nutrient recovery also encompasses the "yuck factor" for both the end users using modified toilet designs, seen at a global scale[78–80] and in Sweden[81], and for farmers who are deciding whether to use the product for food-producing crops[65,78,79,81,82]. Legitimation activities intersect numerous markets; the initial buy-in from agricultural sector, building sector, and politicians is difficult without a strong case for the economic bottom-line, as was observed in Finland, Sweden, and The Netherlands[30,83–85].

These alternative water systems also have a different user experience, requiring additional education and awareness to solicit public support from end users, as described broadly[79,80] and in a case study in Sweden[81]. Engineers and designers for these projects also require increased education and awareness activities otherwise they will resort to technology they are comfortable with that is in line with the conventional, centralized systems to avoid additional risk[30,65,79,85]. These factors of public and sectoral legitimacy subsequently affect resource mobilization and available funding incentives for projects, hindering the market development. Another inhibition is due to strict regulations; in Finland, it was suggested that standards for nutrient recovery are not even attainable for centralized treatment processes[78]. Note that the widespread low-tech and unregulated practices of wastewater reuse in developing countries were outside the scope of this study; however, such technologies highlight the financial affordability and equity dimensions (table 1) and further investigation is strongly encouraged.

## DISCUSSION: INSTITUTIONAL BARRIERS AND SOCIO-TECHNICAL COMPLEXITY OF DIFFERENT ON-SITE TECHNOLOGIES

Patterns from these findings reveal that institutional barriers and socio-technical complexity systematically differ between different on-site UWM approaches (fig. 2). Using rainwater for landscaping is a rather incrementally novel practice that aligns relatively well with the taken-for-granted regime structure in the UWM sector. It can be supported with rather minimal shifts in pre-existing institutions and governance arrangements, for example, by creating targeted financial incentive schemes (e.g. subsidies).

In contrast, technological configurations like urine separation or composting toilets struggle with a highly complex mix of institutional barriers that touch on almost all dimensions of our framework, ranging from *Financial Investment* to *Legal and Regulatory Frameworks*, *Legitimacy*, and *Market Structures* (fig. 1, table 3). Alternative water systems that use greywater for NPR lie somewhere in between the two extremes, with key barriers mostly covering *Legal and Regulatory Frameworks* as well as *Knowledge and Capabilities*.

Figure 2 illustrates our suggestion for the relationship between types of barriers and socio-technical complexity for different on-site UWM solutions. Each of the axes contains a gradient of inherent socio-technical complexity. On the x-axis, complexity increases as the source contains more pollutants, creating a greater potential health risk and requiring additional treatment steps and/or complex user interfaces and monitoring systems. On the y-axis, complexity increases as the recovery purpose moves from non-potable to more complex forms of reuse, to recycling side-products in a different sector (agriculture). Socio-technical complexity increases as the work needed to create or incrementally change the governance structure also increases. Greywater reuse, as seen in Spain[74], England[59], and the United States[27,45,60], has required additional regulatory development for these systems and extensive program support for defining roles and responsibilities in the adjusted permitting pathways. Nutrient recovery, on the other hand, consistently has acknowledged the need for better-defined roles and responsibilities in the UWM, and agricultural sector as a major barrier[28,29,65,81]. Simply put, socio-technical complexity closely correlates with the diversity of institutional barriers within a type of alternative water system and the amount of disruption or adjustment needed in its accompanying governance structure. This relationship further demonstrates the interdependency of dimensions associated with the institutional support structure, as discussed in the point of departure. As complexity increases, so does the necessity of creating or strengthening the various dimensions associated with the uptake of a particular alternative water system.

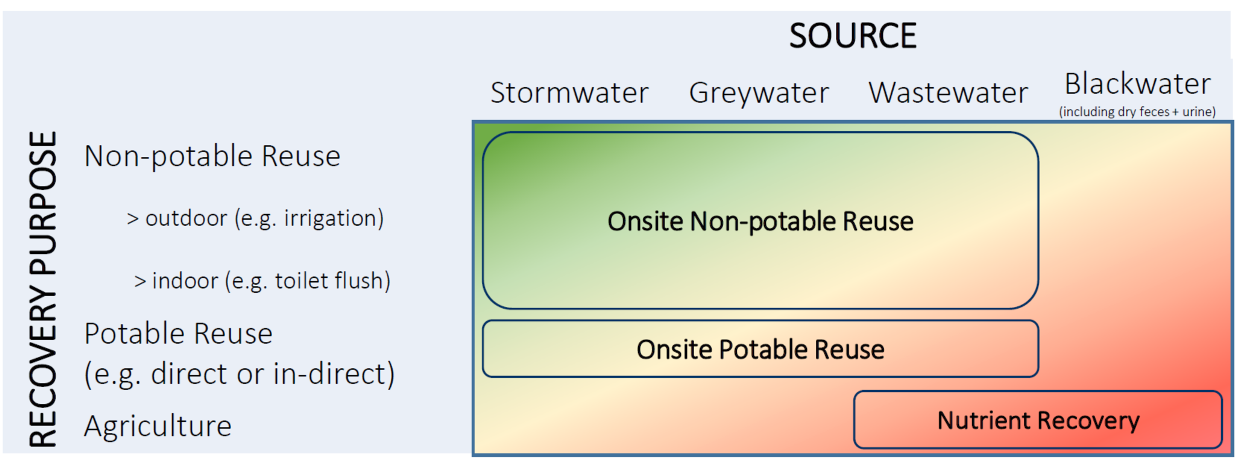


**Figure 2.** Socio-technical complexity, mapped as the number of consistent institutional barriers across various types of alternative water systems.

Understanding this relationship between various alternative water systems and their institutional barrier constellations and socio-technical complexities has important theoretical and practical implications. Theoretically, the connection between institutional barriers and socio-technical complexity equips researchers with the means to construct hypotheses on how transition trajectories differ between different alternative water systems. For stormwater use, transition trajectories that largely align new technologies with existing regime structures, looks plausible. For source separation, in contrast, transitions will depend on the active creation of a highly complex supportive innovation system structure and interventions that disrupt taken-for-granted institutions (e.g. creating new regulatory frameworks or financial incentives to encourage market formation across agricultural and utility industries). Existing literature that covers transitions to on-site alternative water systems (e.g. in Australia, the USA or EU) could mobilize our insights to develop more fine-grained conceptual frameworks on the barriers and enablers of transformative change for different types of UWM solutions[34,86,87]. The perspective developed here furthermore point toward a new research agenda that further unpacks the role of institutional complexity in UWM transitions[88,89].

Practically, findings from this study provide stakeholders interested in adopting on-site technologies with a high-level understanding of the main institutional challenges that will need to be accounted for specific technological solutions. Localities already involved in the adoption process can use these findings as a diagnostic tool for their programs and governance structure to assess if there are unaddressed areas for improving the technology diffusion process. This study does not suggest that complexity should deter adoption, but rather that the actors pushing for disruptive innovation should be strategic about addressing the institutional barriers that are most salient for a specific type of alternative water system. It also implies that the more complex the institutional barriers are the more collective and long-term (policy) strategy is needed in building each dimension to avoid barriers and to develop a governance arrangement that nicely aligns the activities in different parts of the underlying innovation system.

Future work could venture in the following directions that are downplayed in the current study. First, the scope of the analyzed articles was limited to peer-reviewed journal articles in English, excluding other valuable sources of information, such as books, policy documents, and grey literature from potential lead markets in other languages (e.g., Swedish, German, Japanese). Analyzing these additional resources would be a valuable opportunity for future work. One could also expand the analysis beyond the rather narrow focus on urban, on-site reuse to include articles dealing with rural or municipal-scale reuse systems. Additionally, the conceptual framework (table 1) is applied to discuss institutional barriers for alternative water systems; an opportunity exists to similarly explore the enabling factors within each of these dimensions. Finally, equity is identified as a key non-technical dimension (table 1); however, there is a limited body of literature available that covers equity implications of an imminent transition to on-site UWM systems. Additional opportunities exist to expand on this important theme through further empirical investigation.

## SUPPORTING INFORMATION

Appendix A: Visual representation of key dimensions for UWM innovation

Appendix B: Overview of key search terms used in literature retrieval process

Appendix C: Summary of literature retrieval process

Appendix D: Detailed literature retrieval process

Appendix E: Geographic distribution of intermediate aggregation of literature

Appendix F: Final list of articles

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**Author Contributions**

The manuscript was written through contributions of all authors. All authors[ǂ] have given approval to the final version of the manuscript. Miriam Hacker completed data analysis and took the lead role in developing the manuscript. Christian Binz structured the conceptual framing and overall line of argumentation.

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## ABBREVIATIONS

UWM, urban water management; NPR, non-potable reuse; TIS, technological innovation system

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