Identifying Strategies for Implementing Potable Water Reuse Projects: Cross-Case Evidence on Successful Implementation Pathways

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Research Problem Statement

Potable water reuse, which involves treating municipal wastewater to drinking-water standards for indirect or direct augmentation, has become an increasingly promising strategy to enhance water supply reliability under long-term water supply uncertainty.[1,2] Although advanced treatment technologies and risk management- guidance are well established, many potable reuse projects fail to progress beyond planning and design. Projects may stall due to regulatory hurdles, inter-organizational coordination challenges, public opposition, leadership turnover, long project timelines, or funding shortfalls, even when technical feasibility is not in question.

Research Objectives

The objective of this study is to explain why some potable reuse projects achieve successful implementation while others remain unsuccessfully attempted. Through a cross-case analysis, we seek to identify combinations of organizational, institutional, socio-political, and financing conditions associated with implementation success. We ask:

- What combinations of conditions are sufficient for successful potable reuse implementation?
- Which conditions are shared across successful pathways, and which conditions provide alternative strategies to successful implementation that vary by context?
- What project organization conditions influence outcomes when state-level regulatory contexts are comparable?
- How does timing of key decisions, such as public acceptance approaches, influence implementation outcomes?

Research Methodology and Approach

Research Context

We conducted this study within the United States where many regions, particularly in the west and southwest (e.g., California, Arizona, Nevada), are facing significant water scarcity due to prolonged droughts, over-extraction of groundwater, and the impacts of climate change.[3] This scarcity is further exacerbated due to rapid urban growth[4,5] intensifying the demand for potable water even in water-rich

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states (e.g., Virginia, Oregon), making sustainable water management practices like potable reuse increasingly vital.[1,6,7] While the United States is at the forefront of developing and implementing innovative water treatment technologies essential for potable reuse, several projects in the country entered the planning and design phases of implementation but were halted due to regulatory hurdles,[8–10] negative public perception[11–13] or funding deficits,[14–16] leading to sunk costs. Therefore, the United States provided a unique landscape to understand the implementation success of potable reuse projects to sustain future implementation success.

Data Collection

We conducted case studies of sixteen potable water reuse projects across the United States, by purposively selecting cases that had advanced beyond conceptual discussion into formal project planning and represented variation in geography, regulatory setting and implementation outcome. Our final sample included nine successful and seven attempted cases. Successful cases were defined as being operational for longer than one year or had started construction for full-scale operation. Attempted cases were defined as those that were delayed indefinitely or cancelled.

For each case, we triangulated evidence through a systematic analysis of: documentation (e.g., project reports, feasibility analyses, environmental assessments; regulatory documents such as laws/guidance and operator/public engagement requirements; and media articles including local news coverage and social media); semi-structured interviews with key implementers (e.g., utility project managers, consulting engineers, operations and maintenance staff) focusing on project overview, stakeholder engagement, policy/regulation, and resources/funding; and site visits for field observation of water and wastewater facilities to complete interviews by engaging with utility staff informally and gaining contextual insights. We transcribed interviews using the Trint transcription software[17] and imported the combined data for each case into Lumivero NVivo v15[18] for compilation and qualitative coding of transcribed interviews and documentation. Finally, we conducted a cross-case comparison using fuzzy set qualitative comparative analysis (fsQCA).

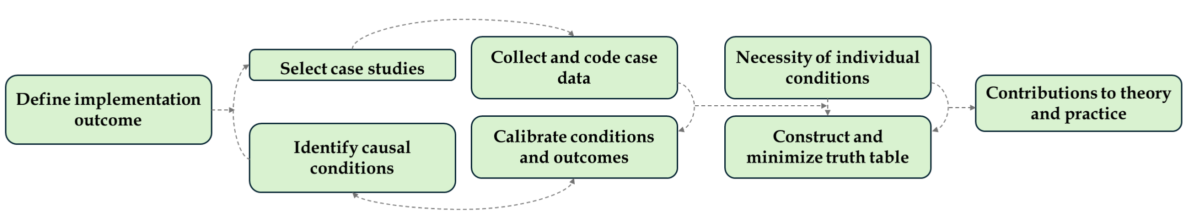

Figure 1. Overall methodological and analytical process.

Data Analysis: Factor Identification, Calibration and fsQCA

We identified causal conditions using thematic analysis,[19] by iteratively refining our codebook derived from potable reuse implementation literature based on emergent case knowledge, and choosing conditions where we saw variation in fuzzy scores across all 16 cases. The resulting ten causal conditions represented institutional, organizational, social, and economic dimensions of implementation. These conditions were: *committed interagency agreements*, *continuity in project leadership*, *sufficient operator training*, *positive media coverage*, *low infrastructure integration burden*, initiating *public education at least 24 months pre-decision*, *local endorsement from community spokespersons, having a permanent demo/visitor center, having sufficient external public capital expenses (CAPEX) funding and having sufficient internal/private CAPEX funding.*

We calibrated the ten causal conditions as fuzzy sets[20] by assigning graded set membership scores (between 0 to 1) to represent the degree to which each causal condition was present (or absent) in each case, using qualitative evidence to indirectly calibrate eight causal conditions, and quantitative data to directly calibrate two causal conditions.[21] . For implementation outcomes, we assigned a score of 1 for successful cases and 0 for attempted cases.

Finally, we constructed the calibrated data matrix (Figure 2) which served as the basis for constructing the fsQCA truth table. Following standard fsQCA procedures, we constructed a truth table, specified directional expectations, and minimized condition combinations using Boolean algebra and fuzzy logic to identify combinations of conditions sufficient for successful implementation (i.e., success pathways).[20,22] We assessed the robustness of our results via sensitivity analysis: re-estimating solutions under alternative truth-table consistency thresholds (0.70 and 0.90 versus the typically used 0.80) which yielded identical pathway solutions and case coverage. The minimized solution produced recurring configurations rather than case-specific patterns, and the pathway structure remained unchanged across robustness checks.

Case No.	Causal Conditions									
	Committed Interagency Agreements	Continuity in Project Leadership	Sufficient Operator Training	Positive Media Coverage	Low Infrastructure Integration Burden	Public Education ≥12 Months Pre-decision	Local Endorsement from Community Spokespersons	Permanent Demo/Visitor Centre	Sufficient External Public CAPEX Funding	Sufficient Internal/Private CAPEX Funding
Necessity consistency	0.96	**0.93**	0.83	0.71	0.63	0.67	0.63	0.56	0.69	0.41
Necessity coverage	0.67	**0.78**	0.84	0.66	0.61	0.69	0.71	1.00	0.89	0.90
Successful Cases (μ=1)										
Case 1	1	1	0.70	1	0	0.67	0.33	0	0.11	0.99
Case 2	1	1	1	0.67	0.67	0.33	1	1	0.99	0.10
Case 3	0.67	0.70	0.70	0.67	0.33	1	0.67	1	0.07	0.99
Case 4	1	1	1	0.67	0.67	1	0.67	0	0.97	0.48
Case 5	1	1	1	0.67	1	1	0.33	0	0.99	0.04
Case 6	1	1	1	0.67	0.67	0.33	0.33	1	0.99	0.04
Case 7	1	1	0.70	0.67	0.67	0.33	0.67	1	0.99	0.04
Case 8	1	0.70	0.70	0.67	1	1	1	1	0.04	0.99
Case 9	1	1	0.70	0.67	0.67	0.33	0.67	1	0.99	0.04
Attempted Cases (μ=0)										
Case 10	1	0.70	0	0.33	1	0	0.33	0	0.10	0.04
Case 11	0	0	0	0	0.33	0.33	0.33	0	0.04	0.04
Case 12	0.33	0.70	0	0.33	0	0.33	0.33	0	0.04	0.10
Case 13	1	1	0.70	0.67	1	1	0.67	0	0.07	0.07
Case 14	0.33	0	0	0.33	0	0.67	0.33	0	0.04	0.04
Case 15	0	0	0.70	0.67	0.67	0.33	0.33	0	0.07	0.07
Case 16	1	0	0	0.33	0.67	0	0	0	0.43	0.07

Fully in-set Partially in-set Partially out-of-set Fully out-of-set

Figure 2. Data matrix with the fuzzy scores for each case's outcome and causal condition. Necessity scores for the presence of individual causal conditions are displayed below each condition.

Key Findings

Descriptive contrasts among causal conditions motivate analysis of combinations of conditions

The calibrated data matrix (Figure 2) indicated that several organizational conditions differentiated successful from attempted cases. For example, *committed interagency agreements* and *continuity in project leadership* showed very high membership across successful cases. In contrast, the same conditions exhibited lower and more heterogeneous membership for attempted cases. These descriptive patterns across causal conditions indicated why individual causal conditions were insufficient to explain the implementation outcome. Instead, implementation success was found to be driven by combinations of institutional and organizational factors, which motivated the need to conduct a cross-case comparative analysis.

Four success pathways were found sufficient for successful implementation across contexts

We identified four success pathways, which were distinct combinations of causal conditions, that were sufficient to achieve successful potable reuse implementation and covered all successful cases (Figure 3). Collectively, these pathways achieved very high overall solution consistency (0.99) and high overall solution coverage (0.67), indicating that cases exhibiting these configurations consistently resulted in success and that most successful cases aligned with at least one pathway.

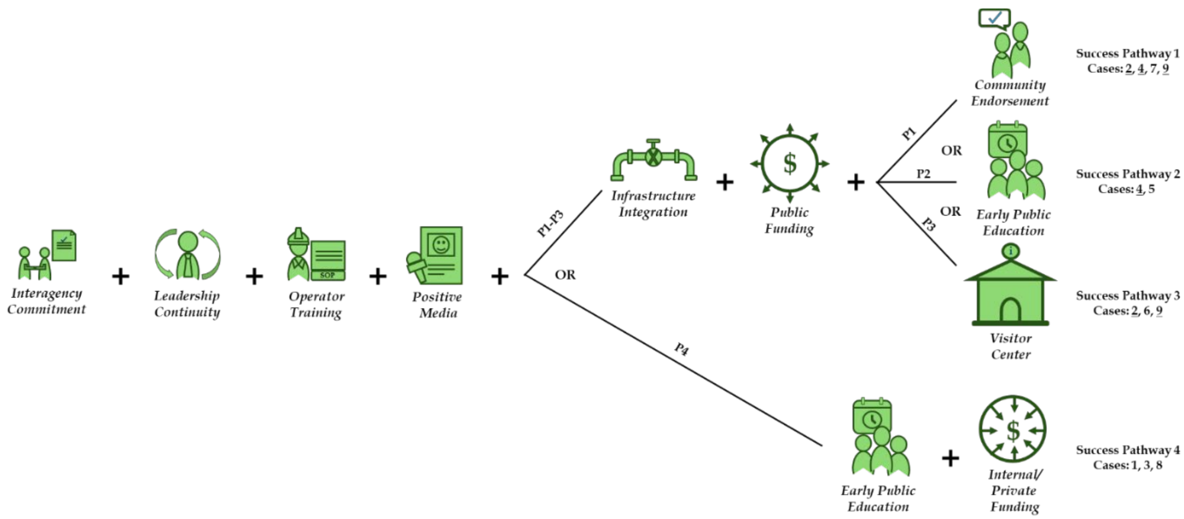

Figure 3. Four success pathways (labeled P1 to P4) showing the combination of causal conditions associated with successful potable reuse implementation (solution consistency = 0.99; solution coverage = 0.67). There are four shared conditions before the pathways branch. Conditions are ordered from left to right by their common presence in the pathways, followed by necessity scores. Pathways are arranged from top to bottom based on pathway coverage scores and by shared conditions rather than chronology. Cases with the conditions on each path are displayed next to the pathways they followed. Underlined case numbers (2, 4 and 9) show cases that followed multiple pathways (i.e., they had all conditions present in the associated pathways).[23]

All four success pathways shared the same four conditions: *committed interagency agreements*, *continuity in project leadership*, *sufficient operator training*, and positive *media coverage*. This shared foundation of causal condition indicated generalizable project organization design logic: successful implementation repeatedly depended on (i) governance arrangements that clarified authority or responsibility and pre-committed partners, (ii) leadership continuity that sustained multi-year and multi-stakeholder coordination, (iii) workforce readiness for advanced water treatment operations that ensured regulatory compliance and political will, and (iv) an information environment robust enough to avoid a lack of social legitimacy (i.e., negative framing such as "toilet-to-tap"[24–26]). More broadly, the findings contribute to engineering project organization research by showing that implementation success in technically mature but institutionally complex infrastructure systems depends on how governance, leadership continuity, workforce readiness, and legitimacy-building are configured across organizational boundaries.

Successful cases combined several mechanisms to ensure the shared conditions were achieved in practice. A common mechanism was establishing *committed interagency agreements* that enclosed partner commitments and lowered implementation risk by defining roles for authority, financing, operations, and permitting. Two agreement types were most common. One, delivery/purchase agreements, which formalized water purchase and exchange commitments that enabled financing and operational planning. For example, in Case 8, private developers contributed capital and funded O&M for the delivery infrastructure, while the utility committed to priority delivery of a specified volume and quality of reuse water. Another, joint regulatory agreements, which aligned permitting sequences and clarified agency responsibilities, helping streamline regulatory approvals and manage shared compliance requirements. For example, in Case 6, a joint regulatory program secured access to augmentation points and conveyance easements, ensured secondary-effluent inflows, and coordinated monitoring and reporting. By contrast, Cases 4, 5, and 7 operated without interagency agreements; these projects relied largely on city council authorization, leaving decision authority and accountability concentrated within a single utility.

Beyond the shared foundation of causal conditions, pathways branched into alternative strategies that reflected differences in financing, infrastructure integration, and additional public acceptance approaches. P1–P3 (first three pathways) combined the shared causal conditions with a *low infrastructure integration burden*, having *sufficient external public capital expenses (CAPEX) funding*, and one of three public acceptance approaches: (P1) having *local endorsement from community spokespersons*, (P2) initiating *public education at least 24 months pre-decision* (i.e., the decision to implement potable reuse at full-scale), or (P3) having a *permanent visitor/demonstration center*. For example, Case 4 was primarily funded by grants that did not need to be repaid; this case's lower infrastructure integration burden made it feasible to cover the remainder of the CAPEX through internal utility enterprise funds. This case also achieved *local endorsements from community spokespersons* by engaging physicians, public health officials, and university researchers to participate in public town halls and by translating reuse treatment terminology into lay terminology. P4 (fourth pathway) combined the shared causal conditions with initiating *public education at least 24 months pre-decision* and having *sufficient internal/private CAPEX funding*. For example, in Case 1, the utility's boards of directors decided to allocate *sufficient internal CAPEX funding* to the project, which was enabled by *continuity in project leadership*. Additionally, early timing of evidence-first public education efforts allowed the utility to use piloting data to answer anticipated questions about topics such as the potable reuse advanced treatment's ability to remove contaminants. P4 suggests a distinct internally financed implementation pathway in which utilities with sufficient financial autonomy can reduce dependence on external public grants, provided that internal capital commitment is paired with early public education and the same core governance, leadership, workforce, and media conditions shared across all successful pathways. For example, Cases 1 and 3 in this pathway exhibit how, even with a non-trivial infrastructure integration burden, utilities with sufficient internal/private CAPEX funding were able to successfully implement potable reuse, primarily through having strong, committed interagency agreements in place.

Ongoing work

Ongoing analyses trace project-phase sequencing to assess how regulatory context and decision timing shape pathway enactment. This analysis entails analyzing cases by project phase (i.e., initiation/conception → pre-planning and scoping → feasibility → detailed design), explicitly connecting not only which conditions were present across cases, but when they occurred relative to key decisions (i.e., Phase 3, which is the phase where the first design-build/design-bid-build award decisions were made). This analysis is strongly motivated by our interpretation of the identified success pathways. For example, case knowledge dictated that we examine the sequencing of public acceptance approaches because cases sometimes appear in multiple pathways, thereby suggesting substitutability among public acceptance approaches that may depend on condition sequencing even for the same successful implementation outcome. Further, this analysis, combined with the state-by-state analysis, will allow us to investigate whether the pathways are context-contingent, i.e., whether state institutional environments moderate the importance of casual condition timing and sequencing, helping explain pathway equifinality and strengthening the external validity of the fsQCA findings.

Implications

Implications for engineering project organization and design for transformation

Potable reuse success is often narrated as a technology adoption problem. Our findings reframe it as a project organization design problem. The shared foundation of causal conditions emphasizes that implementation hinges on deliberately designing inter-organizational governance, leadership structures that ensure continuity, and workforce capability-building systems, alongside proactive management of social legitimacy through media narratives. For engineering project organizations, these findings suggest that success in long-horizon socio-technical infrastructure projects depends on early assembly of durable interorganizational commitments, leadership continuity, operational capability, and social legitimacy.

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