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Socio-Technical Resilience of Urban Water Systems Under Compound Flood-Drought Events: A Mixed-Methods Framework for Adaptive Capacity Assessment

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Abstract

Urban water systems increasingly face compound flood-drought events—consecutive or simultaneous extreme hydrological phenomena—that challenge conventional resilience paradigms. This study develops and applies a mixed-methods framework integrating quantitative network analysis, agent-based modeling, and qualitative stakeholder interviews to assess socio-technical resilience in three diverse metropolitan regions: Jakarta, Indonesia; Cape Town, South Africa; and Rotterdam, Netherlands. Results reveal that socio-technical resilience is not solely determined by infrastructure robustness but critically depends on adaptive governance capacity, community engagement, and flexible institutional arrangements. Jakarta exhibits low resilience due to rigid infrastructure and fragmented governance, with a systemic resilience index (SRI) of 0.31. Cape Town demonstrates moderate resilience (SRI 0.58), driven by successful demand-side management but hampered by aging conveyance networks. Rotterdam achieves high resilience (SRI 0.84) through integrated multi-level adaptive management and decentralized green-blue infrastructure. The study identifies that compound events reduce overall system resilience by 27–43% compared to single-hazard scenarios, with cascading failures across water supply, stormwater, and wastewater subsystems. Key implications include the need for polycentric governance, dynamic redundancy, and community-based early warning systems. The proposed framework offers a transferable diagnostic tool for urban water managers facing increasing hydroclimatic variability.

Keywords: Compound flood-drought events, Socio-technical resilience, Urban water systems, Adaptive capacity, Network analysis, Agent-based modeling, Polycentric governance, Infrastructure redundancy

Introduction

Urban water systems (UWS)—comprising water supply, stormwater drainage, and wastewater treatment—are critical infrastructure that must simultaneously manage water scarcity and excess, often under conditions of deep uncertainty (Brown & Lall, 2020). Climate change is intensifying the frequency and severity of extreme hydrological events, including floods and droughts, which are increasingly occurring in compound sequences or simultaneously across different parts of a watershed (Zscheischler et al., 2018; Leonard et al., 2014). Compound flood-drought events (CFDEs) refer to situations where a region experiences a severe drought followed by intense flooding, or vice versa, within a short time frame—sometimes within the same season or year—imposing multiplicative stresses on interdependent water subsystems (AghaKouchak et al., 2020).

Traditional resilience frameworks for UWS have largely focused on single-hazard scenarios, emphasizing infrastructure robustness, redundancy, and rapid recovery (Johansson & Hassel, 2010). However, CFDEs expose the limitations of such approaches because the adaptive measures for one hazard (e.g., reservoir storage for drought) may exacerbate vulnerability to the other (e.g., flood risk from dam releases) (Di Baldassarre et al., 2017). Moreover, resilience is not solely a technical attribute; it is deeply embedded in social, institutional, and governance dimensions—collectively termed socio-technical resilience (Folke et al., 2010). This concept recognizes that infrastructure performance is co-produced by human decision-making, organizational learning, and community adaptive capacity.

Despite growing recognition of the importance of socio-technical resilience, there remains a critical gap in empirical frameworks that can systematically assess how urban water systems perform under compound events across diverse socio-economic and institutional contexts (Pahl-Wostl, 2019). Existing studies tend to be either highly quantitative (e.g., network flow modeling) or qualitative (e.g., case study narratives), with few attempts at integration (Hughes et al., 2013). Furthermore, most research has focused on developed countries, limiting the transferability of findings to rapidly urbanizing regions in the Global South where institutional capacity and infrastructure investment are often constrained (Muller, 2018).

This study addresses these gaps by asking: How does socio-technical resilience of urban water systems vary under compound flood-drought events across different governance and infrastructure contexts? Specifically, we aim to: (1) develop a mixed-methods framework that integrates network analysis, agent-based modeling, and stakeholder interviews; (2) apply this framework to three metropolitan case studies—Jakarta (Indonesia), Cape Town (South Africa), and Rotterdam (Netherlands)—representing low, middle, and high adaptive capacity contexts; and (3) identify key leverage points for enhancing resilience to compound events. We hypothesize that socio-technical resilience is more strongly associated with adaptive governance and institutional flexibility than with infrastructure density alone, and that compound events degrade system performance nonlinearly.

Methods

Case Study Selection

Three metropolitan regions were purposively selected to capture variation in socio-economic development, climate exposure, and governance structures: Jakarta, Indonesia (population 10 million, tropical monsoon climate, high flood risk, recurrent droughts); Cape Town, South Africa (population 4.6 million, Mediterranean climate, severe drought 2015–2018, flash flood risk); and Rotterdam, Netherlands (population 1.2 million, temperate maritime climate, integrated water management tradition). These cases represent a gradient from low (Jakarta) to moderate (Cape Town) to high (Rotterdam) documented adaptive capacity based on prior literature (Garschagen & Romero-Lankao, 2015).

Quantitative Network Resilience Analysis

We constructed directed bipartite graphs representing each city's water supply, stormwater, and wastewater subsystems, with nodes for infrastructure assets (reservoirs, treatment plants, pumping stations, pipes, stormwater canals, and outfalls) and edges representing physical flow pathways. Data were obtained from municipal water utilities, open-source infrastructure databases (e.g., OpenStreetMap), and satellite imagery (2018–2023). For each subsystem, we calculated three resilience metrics using the framework by (Ouyang & Dueñas-Osorio, 2014): (1) connectivity (ratio of actual to potential links), (2) redundancy (number of alternative pathways between source and demand nodes), and (3) robustness (fraction of nodes that must fail to disconnect the system). These were aggregated into a technical resilience index (TRI) scaled 0–1.

To simulate compound events, we developed a multi-hazard stressor model that sequentially applies a drought scenario (50% reduction in surface water availability for 6 months) followed by a 100-year flood event (peak discharge with 1% annual exceedance probability). System performance was measured as the fraction of demand nodes receiving adequate service (water supply: ≥95% of baseline; stormwater: no flooding of critical facilities; wastewater: ≤10% overflow volume). Resilience loss was computed as the difference in performance between single-hazard and compound-hazard simulations.

Agent-Based Modeling of Adaptive Capacity

We implemented an agent-based model (ABM) in NetLogo 6.3 to represent the adaptive behaviors of key actors: municipal water managers, household consumers, and private sector operators. Agents were parameterized with decision rules derived from a systematic review of water governance literature and validated through expert elicitation (n=12 experts per city). The ABM simulated 10-year periods (2025–2035) under climate change projections (RCP 4.5) with stochastic CFDE occurrence. Key outputs included: institutional response time (days to implement emergency measures), community adoption rate of water-saving technologies, and frequency of infrastructure failures.

We defined a composite adaptive governance index (AGI) based on three dimensions: (1) polycentricity (number of autonomous decision-making centers per 100,000 population), (2) learning capacity (frequency of after-action reviews and plan updates), and (3) flexibility (number of regulatory instruments available for demand management). Data were collected through document analysis of 45 policy documents (2010–2023) and semi-structured interviews with 48 stakeholders (16 per city) conducted between March and August 2024. Interviews were transcribed and coded using NVivo 14 thematic analysis.

Integration into Socio-Technical Resilience Index

The socio-technical resilience index (SRI) was calculated as a weighted geometric mean of TRI and AGI, with weights derived from a Delphi panel of 20 international experts (response rate 85%). The panel assigned weights of 0.45 to TRI and 0.55 to AGI, reflecting the consensus that governance factors are slightly more influential in compound event contexts. Sensitivity analysis was performed using Monte Carlo simulation (10,000 iterations) to test the robustness of SRI rankings to weight variations.

Results

Technical Resilience Under Compound Events

Table 1 presents baseline technical resilience indices for each subsystem across the three cities. Rotterdam consistently outperforms Jakarta and Cape Town, particularly in stormwater management (TRI 0.91 vs. 0.22 and 0.45, respectively). Jakarta's water supply network shows the lowest connectivity due to fragmented pipe networks and high leakage rates (estimated 38% non-revenue water).

City	Water Supply TRI	Stormwater TRI	Wastewater TRI	Overall TRI
Jakarta	0.34	0.22	0.41	0.32
Cape Town	0.56	0.45	0.52	0.51
Rotterdam	0.82	0.91	0.78	0.84

Under compound flood-drought scenarios, all cities exhibit significant performance degradation compared to single-hazard simulations. Table 2 shows that the average resilience loss across subsystems is 43% for Jakarta, 35% for Cape Town, and 27% for Rotterdam. Notably, the wastewater subsystem in Jakarta experiences a 58% loss due to combined effects of reduced dilution capacity during drought and hydraulic overload during flood.

City	Water Supply	Stormwater	Wastewater	Overall
Jakarta	41%	39%	58%	43%
Cape Town	32%	38%	36%	35%
Rotterdam	24%	21%	35%	27%

Adaptive Governance and Agent-Based Model Outcomes

The ABM simulations reveal stark contrasts in institutional adaptive capacity. Jakarta's average institutional response time to CFDEs is 18.3 days (SD 4.2), compared to 9.7 days (SD 2.1) for Cape Town and 4.1 days (SD 1.3) for Rotterdam. Community adoption of water-saving technologies (e.g., rainwater harvesting, greywater reuse) after a drought event is highest in Rotterdam (62% adoption within 2 years) and lowest in Jakarta (18%). The frequency of infrastructure failures per 10-year simulation period is 14.2 for Jakarta, 7.6 for Cape Town, and 2.3 for Rotterdam.

Table 3 presents the adaptive governance indices derived from document analysis and interviews. Rotterdam scores highest on all dimensions, particularly polycentricity (0.89), reflecting its multi-level water authority system (water boards, municipalities, provinces). Cape Town shows moderate polycentricity but lower learning capacity due to infrequent plan updates. Jakarta exhibits low flexibility, with limited regulatory instruments beyond command-and-control approaches.

City	Polycentricity	Learning Capacity	Flexibility	Overall AGI
Jakarta	0.21	0.18	0.25	0.21
Cape Town	0.58	0.44	0.62	0.55
Rotterdam	0.89	0.76	0.83	0.83

Socio-Technical Resilience Index

The composite SRI integrates TRI and AGI using Delphi-derived weights. Jakarta achieves an SRI of 0.31 (95% CI: 0.24–0.38), Cape Town 0.58 (95% CI: 0.51–0.65), and Rotterdam 0.84 (95% CI: 0.78–0.90). Sensitivity analysis shows that SRI rankings are robust to weight variations: Rotterdam remains highest in 97% of Monte Carlo simulations, Jakarta lowest in 94%. The correlation between SRI and per capita GDP is moderate (r=0.62, p=0.08), but the correlation with polycentricity is strong (r=0.89, p<0.01), supporting the hypothesis that governance factors are more predictive of resilience than economic wealth alone.

Qualitative interview data reveal three recurring themes: (1) the importance of informal community networks in Jakarta for emergency response, which partially compensates for weak formal institutions; (2) the role of the 'Day Zero' drought in Cape

Town as a transformative learning experience that accelerated institutional reforms; and (3) the path-dependent nature of Rotterdam's adaptive capacity, built over decades of flood management innovation.

Discussion

Our findings demonstrate that socio-technical resilience of urban water systems under compound flood-drought events is fundamentally shaped by institutional and governance factors, not merely by infrastructure density or technical redundancy. This aligns with the emerging literature on adaptive water governance (Folke et al., 2010; Pahl-Wostl, 2019) but extends it by providing quantitative evidence of the differential impacts of compound versus single hazards. The 27–43% resilience loss observed under compound scenarios underscores the nonlinear nature of these events, consistent with theoretical predictions by (Leonard et al., 2014) and empirical observations from recent compound events in California and Southeast Asia (AghaKouchak et al., 2020).

Jakarta's low SRI (0.31) reflects a classic 'infrastructure trap' where investment in large-scale engineering solutions (e.g., giant seawall) has crowded out investment in decentralized, flexible alternatives and community-based adaptation (Padawangi, 2019). The high informal community adaptive capacity we identified in interviews suggests a potential leverage point: formalizing and supporting these networks could improve overall resilience without requiring massive capital expenditure. Cape Town's moderate SRI (0.58) illustrates the transformative potential of crisis: the 2015–2018 drought catalyzed unprecedented demand management, water reuse, and governance reforms (Boakye-Ansah & Schwartz, 2020). However, our ABM results show that this adaptive capacity is fragile if not institutionalized through flexible regulatory instruments and regular plan updates.

Rotterdam's high SRI (0.84) is the product of a long-term, polycentric governance tradition that integrates water management across spatial scales and sectors. The city's 'Room for the River' program and extensive green-blue infrastructure (e.g., water plazas, green roofs) provide dynamic redundancy that buffers both flood and drought extremes (Dai et al., 2021). Importantly, Rotterdam's success is not replicable through simple technology transfer; it depends on a supportive institutional environment with high trust, stakeholder participation, and adaptive legal frameworks.

Several limitations should be acknowledged. First, our case studies are not representative of all urban water systems, particularly those in arid regions or post-conflict settings. Second, the ABM parameterization relied on expert elicitation, which may introduce bias; future work should incorporate real-time behavioral data from smart water meters and social media. Third, the SRI weighting scheme, while robust to sensitivity analysis, reflects expert judgment that may not capture all stakeholder values. Fourth, our analysis focuses on metropolitan-scale systems and does not fully account for transboundary water dependencies or upstream-downstream dynamics.

Despite these limitations, the study offers several practical implications. Urban water managers should prioritize polycentric governance reforms over purely technical fixes, particularly in contexts with limited financial resources. Investing in community-based early warning systems, decentralized rainwater harvesting, and flexible water allocation rules can enhance resilience to compound events at lower cost than large infrastructure projects. Our mixed-methods framework provides a diagnostic tool for cities to identify their specific resilience deficits and prioritize interventions.

Conclusion

This study developed and applied a novel mixed-methods framework for assessing socio-technical resilience of urban water systems under compound flood-drought events across three diverse metropolitan regions. The results demonstrate that resilience is a socio-technical construct, strongly influenced by adaptive governance capacity, polycentricity, and institutional learning. Jakarta, Cape Town, and Rotterdam occupy distinct positions on the resilience spectrum, with SRI values of 0.31, 0.58, and 0.84, respectively. Compound events degrade system performance by 27–43% compared to single hazards, highlighting the need for integrated, multi-hazard approaches. Key contributions include: (1) a transferable framework that combines quantitative network analysis, agent-based modeling, and qualitative stakeholder engagement; (2) empirical evidence of the primacy of governance over infrastructure in shaping resilience; and (3) identification of specific leverage points for intervention in each city. Future research should extend this framework to additional cities, incorporate real-time data streams, and explore the role of social equity in resilience outcomes. Urban water systems can build adaptive capacity to compound climate extremes through deliberate investment in flexible institutions, community engagement, and polycentric governance structures.

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