

Performance-based resilience assessment in integrated water systems: challenges and opportunities

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ABSTRACT

The concept of resilience has been increasingly applied in water systems management and planning. It has been assessed through a ‘performance-based’ approach, which derives resilience metrics from dynamic system behaviour under pressure. However, the application of this approach may face great challenges when applied to integrated water systems, including the complexities in physical processes, diverse management objectives, and siloed practices across subsystems. To assess its feasibility, we review the key elements of the performance-based resilience assessment, including performance indicators, thresholds, and resilience metrics, across urban, agricultural, and natural water subsystems. Eight challenges are identified, primarily focused on deriving consistent results across subsystems and interpreting assessment for actionable management. To address these challenges, a resilience assessment framework for integrated water systems is proposed. This framework applies unified resilience assessment approaches across subsystems to enable intercomparison and synthesises short- and long-term behavioural characteristics through a bottom-up method. Stakeholder engagement is emphasised to validate and iteratively refine assessments, enhancing the effectiveness and applicability. To demonstrate its utility, three potential application scenarios are conceptually designed to (1) quantify co-benefits and trade-offs on a unified scale, (2) evaluate the cost-effectiveness of planning decisions, and (3) guide regional planning based on catchment characteristics. Future research could test these scenarios and generate evidence to enhance decision-making for resilient integrated water systems.

1. Introduction

Maintaining functional and healthy water systems is essential for societal well-being and environmental sustainability (Bhaduri et al., 2016; Liu et al., 2024). However, water systems face increasing pressures from changes in natural (e.g., climate change) and social (e.g., population growth) conditions, often termed ‘stressors’ (Eakin & Luers, 2006). Understanding the impacts of these stressors and the responses of water systems is crucial for effective management and planning.

The application of resilience concepts to water systems has emerged as a response to this challenge (Mugume and Butler, 2017; Quitana et al., 2020), with the key terms summarised in Table 1. Originating from the ecological field, resilience has been adapted for engineered systems, defined as the ability to maintain residual functionality under stressors and rapidly recover normal operations through human intervention (Holling, 1996). To quantitatively operationalise this concept, a widely adopted framework decomposes resilience into four metrics, known as the ‘4Rs’ (Adjetey-Bahun et al., 2014; Cimellaro et al., 2010; Huang

et al., 2021). These four metrics are: *robustness*, the ability to withstand stressors and maintain normal functions; *rapidity*, the ability to timely resume the provision of normal functions from a disruption; *redundancy*, the extent of using alternative resources for preventing losses of functions; and *resourcefulness*, the skills to identify problems and prioritise management under stressors.

A performance-based approach to resilience quantification evaluates the dynamic behaviour of systems under stress, by analysing temporal variations in performance indicators (Bruneau et al., 2003) (Fig. 1(a)). This approach introduces thresholds to distinguish between the normal and vulnerable states (Dakos et al., 2015; Linnenluecke & Griffiths, 2012; Poulin & Kane, 2021). A disruption event is then identified from the onset of system performance deterioration into the vulnerable state to the restoration back to the normal state. The 4Rs metrics can be evaluated based on the shape characteristics of the curve as conceptual analogues, such as duration; frequency, magnitude, slope, and area, which are mapped to directly reflect their definitions above (Roach et al., 2018). For example, Simonovic and Arunkumar (2016) explicitly

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Table 1
Summary of terms and their definitions with examples.

Terms	Definitions
Resilience	The ability to maintain residual functionality under stressors and rapidly recover normal operations through human interventions
• Stressors	Pressures exerted on systems from changes in natural (e.g., climate change) and social conditions (e.g., population growth)
• Resilience metrics	Measures that quantify a system's resilience (e.g., 4Rs)
- Robustness	The ability to withstand stressors and maintain normal functions
- Rapidity	The ability to timely resume the provision of normal functions from a disruption
- Redundancy	The extent of using alternative resources for preventing losses of functions
- Resourcefulness	The skills to identify problems and prioritise management under stressors
• Performance-based resilience assessment	An approach that calculates resilience metrics via evaluating the temporally dynamic behaviour of systems under stressors. It normally identifies the disruption events and gathers shape variables to calculate resilience metrics
• Performance indicators	Variables that characterise the temporal variations of system performance under study (e.g., percentage of demand satisfied for water supply system)
• Thresholds	Values that distinguish the system performance between normal and vulnerable states (e.g., 85 % demand satisfied for water supply system)
• Normal/vulnerable states	Status where systems functionality is satisfactory/unsatisfactory (e.g., above/below 85 % demand satisfied for water supply system)
• Disruption event	An event from the onset of system performance deterioration into the vulnerable state to the restoration back to the normal state (e.g., percentage of demand satisfied drops below 85 % and then returns back to 85 %)
• Shape variables	Variables that describe the shape characteristics of the temporal variations of the performance indicators (e.g., area, duration, magnitude, slope, and frequency)
Integrated water systems	The terrestrial water cycle that encompasses both natural and engineered components, linked through water fluxes as their interactions at a catchment scale
• Components	Entities that process unique behaviour (e.g., reservoir can store and release water, land generates runoff)
• Interactions	Processes that pass physical or information fluxes between components (e.g., abstracted water from groundwater body to freshwater treatment plant, stormwater discharged from sewers to rivers)
• Subsystems	Subsets of integrated water systems comprised of components and their interactions (e.g., water supply infrastructural system, upstream–downstream river system)
• Process complexity	Numerous processes embedded in the integrated water systems that often cause non-linearity and consequential impacts where impacts can propagate from one subsystem to another (e.g., upstream river water abstraction reduces downstream environmental flows and water quality)
• Water management objectives	Goals that aim to be improved specified by diverse water system stakeholders/managers (e.g., infrastructural functionality maintenance, socio-economic well-being improvement, and environmental protection)
• Targeted interventions/planning	Measures or strategies for effectively improving unsatisfactory resilience levels for a specific water management objective (e.g., sustainable urban drainage systems (SuDs) for mitigating urban stormwater and improving urban flood resilience)

established the correspondence by operationalising these metrics as follows (Fig. 1(a)): robustness is measured by the minimum residual function magnitude, directly reflecting its definition as the system's capacity to maintain functionality; rapidity is quantified via total disruption duration, consistent with its conceptual focus on timely

resuming; redundancy is represented by performance deterioration slope, aligning with its role in slowing down losses through alternative resources; and resourcefulness is captured by the recovery slope, corresponding to its emphasis on adaptive problem-solving that speeds up the restoration from disruptions. Although such operationalisation may differ across studies (e.g., variations in shape variables or mathematical expressions for metric calculations in Fig. 1(a)), this approach provides a conceptually coherent and quantifiable characterisation of system behaviour under stressors, facilitating scenario comparisons (Vugrin et al., 2017). It has been widely applied in various water systems across supply (Klise et al., 2017), drainage (Osheen et al., 2023), and river (Hoque et al., 2012), to design management strategies that address future uncertainties and support decision-making.

Recent progress on integrated water resources management (IWRM) has highlighted the benefits of managing all the water systems as a whole for better social and environmental outcomes (Al-Jawad et al., 2019; Bilalova et al., 2023; Liu et al., 2023b). We refer to these individual water systems, which are subsets of integrated water systems, as 'subsystems' in the following text. At a catchment scale, an integrated water system encompasses both engineered and natural components, along with the fluxes linking them within the terrestrial water cycle (Mijic et al., 2024). Compared to isolated subsystems, integrated water systems exhibit new characteristics (Fig. 1(b)): (1) increased process complexity due to various behaviour of components and their interactions across the natural hydrological cycle and built-up infrastructure (Hassanzadeh et al., 2014; Liu et al., 2021); (2) diverse management objectives across the infrastructural functionality (e.g., water supply and availability), socio-economic well-being (e.g., flood mitigation) and environmental protection (e.g., river water quality) (Liu et al., 2023a; Matrosov et al., 2015), and (3) current siloed management practices, where stakeholders focus on individual subsystems, hindering information communication and management coordination (Johannessen and Mostert, 2020; Manny et al., 2022). These characteristics challenge the application of existing performance-based approaches, which are often tailored to specific subsystems and stakeholder objectives. A key challenge lies in the approaches' ability to provide meaningful insights into the intricate dynamics and implications for enhancing system-level outcomes.

This paper aims to explore performance-based resilience assessment in integrated water systems by discussing three research questions:

- What challenges arise when applying current performance-based resilience assessment to integrated water systems?
- How can these approaches be adapted to address challenges and produce reliable resilience results?
- How can these adapted approaches be further applied to enhance IWRM outcomes?

To answer these questions, Section 2 reviews resilience assessments in individual subsystems and identifies key challenges that emerge when extending these methods to integrated systems. To address these challenges, Section 3 proposes a resilience assessment framework that refines the existing approaches for integrated systems. Section 4 demonstrates the framework's decision-support value through outlining application scenarios, particularly in how incorporating resilience assessment could strengthen management coordination for better system-level outcomes. By synthesising conceptual advances with actionable recommendations, this paper presents a literature-based perspective, aiming to advance the alignment of resilience theory with integrated water resources management.

2. Current performance-based resilience assessment for water subsystems

To evaluate the applicability of performance-based resilience assessment in integrated water systems, this study first reviewed existing

studies on engineered (urban supply, drainage, and agriculture) and environmental (river and groundwater) subsystems. An initial search for papers is conducted based on the Google Scholar database using keywords, which are a combination of system category ('water supply', 'drainage', 'agriculture water', 'river high flow OR fluvial flood', 'river low flow OR drought', 'river water quality', 'groundwater') and 'resilience'. Around 30 records per search appearing on the first three web pages are obtained as highly relevant papers. These papers are then subsequently manually filtered based on the two criteria:

- (1) 'The study must adopt a performance-based approach that reveals dynamic system behaviour under stressors';
- (2) 'The study must explicitly develop resilience metrics and apply them to real-world systems with quantitative data analysis'.

The term 'performance-based' was not explicitly used as a search keyword, as some studies have adopted this approach without explicitly mentioning it. This resulted in the inclusion of 41 papers. While not exhaustive, the selected papers provide a proof-of-concept sample for analysing recent resilience assessment trends across subsystems. We believe this sample sufficiently serves the purpose of this study: a cross-subsystem comparison to identify commonalities, differences, and transferable insights in performance-based resilience assessment, as well as key gaps in extending these approaches to integrated systems. This comparative analysis differs from a systematic review that often focuses on cataloguing resilience methodologies within individual subsystems, where a more exhaustive coverage of literature is needed (Juan-Garcia et al., 2017).

Overall, most of the reviewed studies are primarily focused on specific water subsystems, with only three papers attempting partial integration, including supply-drainage (Bouziotas et al., 2023; Schoen et al.,

2015) and land-river (Li et al., 2019). Performance-based approaches are significantly more common for urban infrastructure subsystems (32 papers on urban supply-drainage) compared to the others (6 papers on rivers and groundwater and 3 papers on agriculture). The details of their applications, including performance indicators, thresholds, and resilience metrics, are compared, with details provided in [Supplementary Material 1](#). These applications are conceptually extended to integrated water systems and critically assessed to identify potential challenges. Eight challenges are highlighted specific to the unique characteristics of integrated water systems (Table 2), which are discussed in the following subsections.

2.1. Performance indicators

Different categories of performance indicators have been adopted to illustrate the water subsystem behaviour under stressors. Studies on urban supply and drainage subsystems often adopted indicators describing infrastructural state and service provision. The ratio of supply to demand is the common indicator describing the water supply infrastructure service (Makropoulos et al., 2018; Roach et al., 2018), while combined sewer overflows (CSO) spill and sewer flooding volume are adopted to indicate the drainage capacity (Guptha et al., 2021; Rodriguez et al., 2021). Pollutant concentrations in effluents are common indicators to examine the efficacy of wastewater treatment (Sweetapple et al., 2019), which can alternatively be represented by the failure probability of treatment processes (Holloway et al., 2021). Beyond infrastructural service, some studies on drainage and fluvial flood resilience adopted economic losses to estimate damage to the socio-economic wellbeing (De Bruijn, 2004; De Oliveira et al., 2022), along with farmers' income losses for agriculture water resilience (Balali et al., 2025). In addition, environmental state indicators can be seen in studies

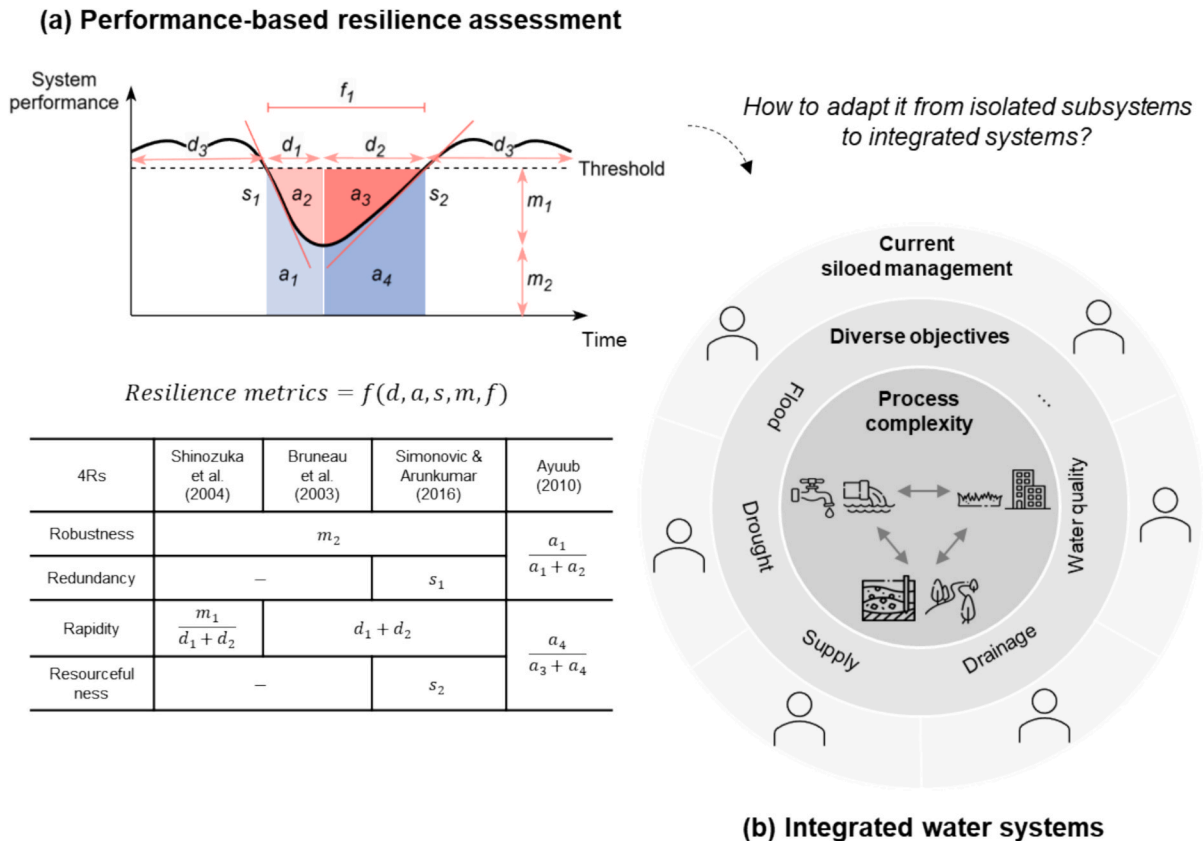


Fig. 1. Performance-based approach for resilience assessment (a) (Shape variables, including duration (d_1, d_2, d_3), frequency (f_1), magnitude (m_1, m_2), slope (s_1, s_2), and area (a_1, a_2), are extracted, with illustrative examples using them to assess the 4Rs (robustness, rapidity, redundancy, resourcefulness) by Shinozuka et al. (2004), Bruneau et al. (2003), Simonovic and Arunkumar (2016), and Ayyub (2014)) and the characteristics of integrated water systems (b).

Table 2
Challenges in resilience assessment for integrated water systems.

Details of assessment applications	Characteristics of integrated water systems	Challenges
Performance indicators	Process complexity creating various behavioural characteristics	1. A single aggregated indicator cannot capture the diverse performance of individual components; 2. Multiple indicators derived from individual subsystem models embed inconsistencies due to different modelling boundaries
Thresholds	Siloed management practices involved with subjectivity and arbitrariness from subsystem stakeholders and researchers	3. Diverging conceptualisation of disruption events (e.g., above or below threshold values) arise from different physical meanings of various system indicators 4. Threshold numbers and values show researchers' subjective resilience conceptualisation and can be sometimes arbitrary, whose impacts on resilience results remain unexplored
Resilience metrics	Diverse management objectives require coordination	5. Various mathematical formulations are used without evaluation of their indication efficacy, posing risks in failing distinguishing subsystem behaviours. 6. Difficulties in agreeing weights for metric synthesis influenced by stakeholders' subjective prioritisation of behavioural characteristics for management. 7. Defining and agreeing on temporal scales for resilience assessment across subsystems is difficult. 8. Interpreting resilience changes and their implications for management and decision-making remains complex and non-straightforward

on natural water bodies (e.g., pollutant concentration in rivers (Hoque et al., 2012) and groundwater levels in aquifers (Sarkar & Chinnasamy, 2023)) or those that view environmental impacts as a key aspect of infrastructure subsystem performance (e.g., river pollutant concentration as a consequence of urban drainage (Casal-Campos et al., 2018)).

Most studies have used a single indicator to represent the whole subsystem's performance (Guptha et al., 2022; Makropoulos et al., 2018; Sarkar & Chinnasamy, 2023). The indicators from different subsystems illustrate distinct behavioural dynamics, which are impacted by the stressor characteristics. For example, water supply deficits induced by droughts took months to recover (Cubillo & Martínez-Codina, 2019), while sewer flooding from extreme rainfall events last several days (Wang et al., 2019). System responses also vary under the same stressor. For example, groundwater levels respond more slowly to meteorological droughts than streamflow due to delayed subsurface processes (Tirogo et al., 2016). Capturing such variability across an integrated water system is infeasible using a single performance indicator (Challenge 1).

Some studies, instead, have included multiple indicators to reveal detailed subsystem performance (Dong et al., 2017; Li et al., 2019). For example, within the urban drainage system, De Oliveira et al., (2022) used housing, sewage, mobility, and community facility indicators to assess flood resilience. A key challenge in applying multiple indicators to integrated water systems lies in simulating the interdependences across

all the subsystems to capture the propagation of stressor impacts (Challenge 2). Using separate models with different boundary conditions can produce inconsistent results, requiring an integrated modeling approach that accounts for cross-subsystem processes (Dobson et al., 2023).

Among the reviewed studies that adopt multiple performance indicators, Casal-Campos et al., (2018) integrated Storm Water Management Model (SWMM) with a wastewater treatment plant model to simulate drainage and water quality impacts, while Bouziotas et al., (2023) adopted Urban Water Optioneering Tool (UWOT) to evaluate integrated supply-drainage resilience. However, these models primarily focus on infrastructure subsystems. Enabling integrated water resilience assessment requires further incorporating natural hydrological processes, including water quantity and quality dynamics, and their interactions with infrastructure systems.

2.2. Thresholds

Performance-based resilience assessments commonly use fixed thresholds to characterise the transitions between normal and vulnerable states. The interpretation of threshold exceedance depends on the performance indicators: For indicators such as flooded volume, CSO spills, and pollutant concentration, disruptions occur when values exceed thresholds (Hoque et al., 2012; Zhang et al., 2021a). On the contrary, for water supply and groundwater level indicators, disruptions are identified when values fall below thresholds (Chinnasamy et al., 2018; Makropoulos et al., 2018). These contrasting scenarios are rarely addressed simultaneously in reviewed studies but are likely present in integrated water systems, which should be equally evaluated to generate comparable resilience results (Challenge 3).

The detailed settings of thresholds are heavily dependent on the researchers' conceptualisation of system states and vulnerability. This dependency firstly affects the number of thresholds defined across subsystems. Most studies employ a single threshold value per indicator, exceeding which signifies system failure (Rodriguez et al., 2021; Sweetapple et al., 2022). However, multiple thresholds can distinguish varying degrees of vulnerability (Wang et al., 2019). For example, Cubillo and Martínez-Codina (2019) categorised the losses of water supply services into standard, normative, accepted, and critical states. In some cases, thresholds are implicitly defined, such as the absence of flooded volume for urban drainage systems (Mugume et al., 2015; Wang et al., 2022) and farmers' normal income in agricultural contexts (Widhianti et al., 2025). Furthermore, only two papers avoided setting disruption thresholds but derived resilience metrics directly from performance indicator variations (Birgani & Yazdandoost, 2016; De Bruijn, 2004).

The subjective conceptualisation of thresholds is influenced by management and design practices. For example, environmental state indicators often use regulatory standards for pollutant concentrations (Hoque et al., 2012; Sweetapple et al., 2022), while drainage systems rely on maximum allowable discharge capacities (Dong et al., 2017; Yazdi, 2018). However, some thresholds are arbitrarily defined without sufficient justifications. For example, Veetil et al., (2018) used Standardised Precipitation Evapotranspiration Index (SPEI) below -1 and duration above two months to define droughts and acknowledged that such criteria vary with stakeholder interests. The effect of such threshold variations on resilience assessments remains underexplored in the literature.

Subjective threshold choices across subsystems challenge robust intercomparison in integrated water systems (Challenge 4). Variations in the number of thresholds reflect different resilience conceptualisations, leading to inconsistent assessments and impeding stakeholder communication. Even with consistent threshold numbers, subjective value choices introduce great uncertainties, influencing disruption identification and shape characteristics (Fig. 1(a)). Looser thresholds may overestimate resilience, while stricter ones underestimate it. This

potentially leads to resilience results misrepresenting subsystem conditions and contradicting stakeholder perceptions. The uncertainty complicates consensus on management priorities and coordination, which is crucial for integrated water resources management.

2.3. Resilience metrics

Performance-based resilience metrics are typically developed from five shape variables, with studies prioritising different combinations (Table S4 in Supplementary Material 1). The most prevalent metric is the area under a system performance curve, especially in urban water supply (Makropoulos et al., 2018; Roach et al., 2018) and drainage systems (Wang et al., 2022; Zhang et al., 2021a). Duration, as the non-disruptive time over the study period (Hoque et al., 2012; Klise et al., 2017), and magnitude, as the maximum performance loss performance (Birgani & Yazdandoost, 2016; Sweetapple et al., 2019), are also widely adopted. Frequency, defined as the event probability (Holloway et al., 2021) or occurrence count (Roach et al., 2018), is less commonly adopted. Slope-based metrics are rare, appearing in only one study as economic damage rate during floods (De Bruijn, 2004). Some studies combine multiple shape variables into a single resilience metric, such as Veetil et al (2018) integrating frequency and duration.

Resilience metrics, often shaped by researchers' subjective designs, vary significantly in their mathematical formulations across subsystems (Juan-Garcia et al., 2017; Liu and Song, 2020). However, their accuracy in capturing system behaviour changes remains unverified. Some metrics exhibit persistently high values under different stressors (e.g., near 1 (Schoen et al., 2015)). This phenomenon creates ambiguity, as it could suggest that the system is constantly resilient or the metric is insensitive to performance changes. Such ambiguity obscures system behaviour analysis and the metrics' utility in evaluating interventions. In integrated water systems, applying such metrics across subsystems may produce similar resilience values despite distinct behaviours, providing limited insights (Challenge 5). Rigorous validation is thus essential to ensure metrics can effectively distinguish subsystem behaviour before management application.

Many studies adopt multiple metrics to evaluate behavioural characteristics (De Bruijn, 2004; Kohler et al., 2020). However, few synthesises them into a scalar measure of whole-subsystem resilience, typically using weighted averages. Weights are often generated using Analytical Hierarchy Processes (AHP) that incorporate expert opinions (Casal-Campos et al., 2018), or assigned arbitrarily (Li et al., 2019)). Although weighting risks information loss (Sweetapple et al., 2019), synthesis remains valuable for integrated water systems, as it reduces redundant information and provides high-level resilience summaries for stakeholder communication. However, stakeholders value metrics differently based on subsystems management priorities. For example, wastewater managers may emphasise treatment failure frequency, while water supply managers focus on overall functionality loss or disruption duration. This divergence complicates consensus on resilience metric weights for integrated water systems. The challenge lies in synthesising metrics to enable cross-subsystem comparisons while preserving the stakeholder-specific behavioural priorities (Challenge 6).

The temporal span of performance-based resilience metrics varies depending on subsystem management objectives. For infrastructure subsystems (e.g., drainage and water supply), resilience is often assessed during short-term disruptions (e.g., hourly design storms or monthly droughts), aligning with operational goals to maintain functionality under transient stressors (Mugume et al., 2014). In contrast, natural subsystems (e.g., groundwater (Hellwig & Stahl, 2018) and river water quality (Martin et al., 2017)) require long-term assessments spanning years or decades, as their delayed responses to interventions demand management strategies focused on preventing gradual degradation (Hoque et al., 2012). To address all the management objectives, resilience assessments in integrated water systems must account for these multiple temporal scales. However, achieving consistent and actionable

resilience insights across these scales for various subsystems remains a significant challenge (Challenge 7).

Finally, while performance-based metrics are valuable for evaluating interventions and management strategies through scenario simulations (Roach et al., 2018), results interpretation remains complex. A key challenge lies in understanding the physical implications of resilience changes (e.g., an increase from 0.7 to 0.8). In integrated water systems with diverse management objectives, this challenge is amplified by the need to compare resilience changes across subsystems. To ensure comparability, unit resilience change (e.g., by 0.1) should represent the same impact across all the subsystems. However, weighted-average resilience metrics complicate this, as equal overall changes can arise from varying contributions of different resilience dimensions (4Rs). This ambiguity in interpreting resilience changes across subsystems hinders communications and coordination among stakeholders (Challenge 8).

3. A proposed resilience assessment framework for integrated water systems

To address the identified challenges (Table 2), we propose a conceptual performance-based resilience assessment framework for integrated water systems (Fig. 2). The framework outlines four iterative steps that suggest exploratory actions, informed by examples from existing literature. Given the diversity of resilience assessment approaches (Section 2), the framework does not prescribe a fixed methodological setting but instead offers generic guidance to accommodate stakeholder preferences. To illustrate potential implementation, we provide a proof-of-concept case study in Supplementary Material 2 to demonstrate one possible application based on our perspective. However, we emphasise that this example is preliminary and lacks comprehensive stakeholder engagement, which is a critical step of framework application. Hence, it serves only as an illustrative example rather than a rigorous validation.

3.1. Uniform resilience conceptualisation across subsystems

This framework starts from conceptualising the resilience for integrated water systems. This step involves identifying subsystems to be assessed and selecting performance indicators that reflect dynamic variations (Fig. 2(a)). Multiple indicators are recommended to be selected to represent various aspects of the performance for each subsystem (Challenge 1). For example, a holistic evaluation of agricultural subsystem resilience could integrate performance indicators such as soil moisture deficit (environmental state) (Rey et al., 2017), irrigation reservoir level (infrastructure services) (Lankford et al., 2023), and farmer income (socio-economic well-being) (Widhiyanti et al., 2025). The conceptualisation process also defines the number and values of thresholds used to characterise normal and vulnerable states across subsystems. To enable fair intercomparison of resilience results, the number of thresholds should be consistent across all indicators.

Using integrated water systems in the UK as an example, current research and management practices have adopted many useful indicators and multi-level standards to assess system vulnerability. For example, river flow statistics, such as the 90th (Q10) and 95th (Q5) percentile flow and the median annual maxima flood (QMED), are used to assess fluvial flood risks (UK CEH, 2022); the standardised groundwater level index measures drought severity (Bloomfield & Marchant, 2013); and the Water Framework Directive (WFD) classifies river water quality into 'poor', 'moderate', 'good', and 'high' statuses (DEFRA, 2014). These indicators and thresholds are generally with adequate scientific justifications, which are good initial choices for supporting reliable assessments for natural water body subsystems (Challenge 4).

To enhance integrated water management, performance indicators and thresholds should also capture subsystem interactions. Environmental flow regimes, for example, link flood and drought resilience by setting seasonal ecological flow targets. Similarly, baseflow and riverbed

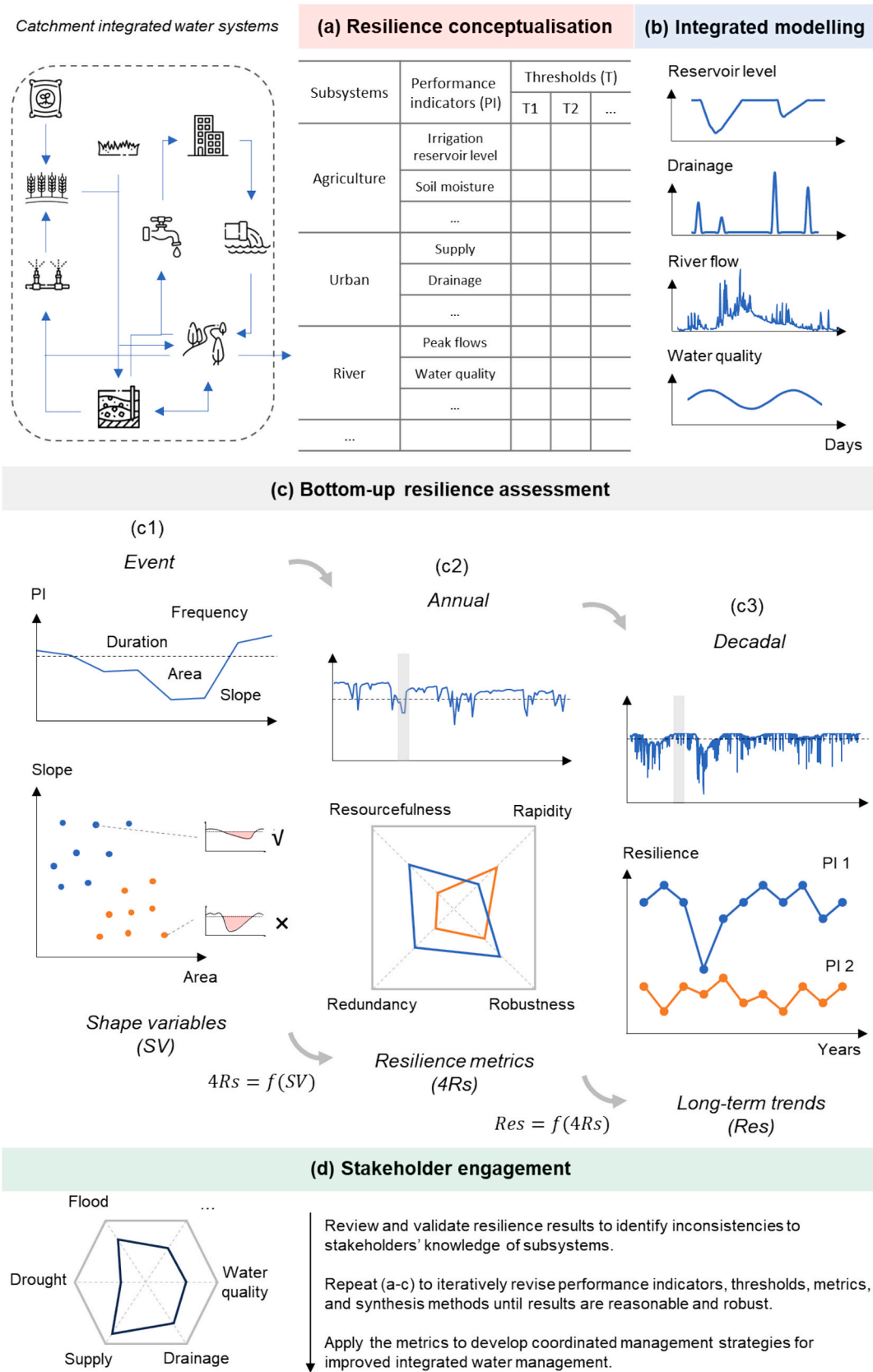


Fig. 2. A potential resilience assessment framework for integrated water systems, including four iterative steps that address the identified challenges in Table 2. It is noted that the temporal scale, shape variables, resilience metrics, and synthesis methods depend on stakeholder decisions and the figure is just a conceptual illustration.

leakage quantify surface–groundwater exchanges, revealing how stressors affect flux dynamics as well as groundwater storage and river flow regimes. Incorporating these indicators could facilitate integrated resilience assessment for broader system-level benefits.

3.2. Integrated modelling simulating subsystem interdependences

To evaluate the performance indicators and reveal their dynamic variations, integrated modelling is then conducted to generate time-series results for individual subsystems (Fig. 2(b)). At the catchment scale, such modelling must simulate both infrastructure (e.g., supply and drainage) and natural water cycles (e.g., surface and subsurface processes), including their interactions in terms of water quantity and quality. By simulating these subsystem interdependencies, it can reveal how stressors impacts propagate through the system. This ability reduces the inconsistencies caused by different boundary conditions adopted by siloed models (Challenge 2).

Integrated modelling for performance indicator evaluation requires aligning simulation timesteps with subsystem resilience assessment temporal scales, ranging from short-term (hourly/daily) to long-term (yearly/decadal) (Challenge 7). Two model coupling approaches could address this requirement. The “loose coupling” approach preserves the original timesteps of subsystem models by linking them via message-passing interfaces (Belete et al., 2017). However, the simulation is constrained by the subsystem models with the finest timestep (e.g., seconds) and thus can be computationally expensive, which requires machine-learning emulators for long-term simulations (Yang et al., 2025). Alternatively, the “tight coupling” approach developed the whole integrated model within a single framework that adopts unified timesteps across subsystem processes. This approach can sacrifice some short-term granularity but enable efficient long-term simulations. For example, the Water System Integration Modelling (WSIMOD) framework simulates daily mass-balance dynamics and thus enables decadal simulations with runtimes of minutes (Dobson & Mijic, 2020; Dobson et al., 2023; Liu et al., 2023b). In summary, choosing the appropriate modelling approach for performance indicator evaluation depends on whether high-resolution dynamics (loose coupling) or computational efficiency for long-term assessments (tight coupling) is prioritised.

Among the evaluated performance indicators, thresholds can be applied to identify disruption events. Since disruption may correspond to values above or below thresholds (Challenge 3), performance indicators should be grouped accordingly. The group of indicators with disruptions occurring above thresholds, such as wastewater CSO spills, sewer flooding, river high flows, and water quality concentrations, can be multiplied by -1 to align with the pattern of indicators where disruptions occur below thresholds. This standardises a consistent system performance curve across all indicators in the resilience assessment and facilitates intercomparison.

3.3. Bottom-up resilience assessment across multiple temporal scales

To address Challenge 7 on the difficulties in defining and agreeing on temporal scales for resilience assessment among subsystems, this framework proposed to conduct resilience assessment across events, years and decades. We believe resilience results across these scales can provide different management insights for short-term operation and long-term planning. To ensure consistency, a bottom-up approach is adopted to assess resilience and integrate findings across the scales, providing a full diagnosis of the whole integrated water system.

(1) Event-scale shape variables

Based on the threshold definitions, the disruption events are delineated for each subsystem performance indicator. Within each event, shape variables are collected to quantify subsystem behaviour, creating a database for analysing their statistical distributions. These

distributions real common response patterns to stressors, helping identify behavioural archetypes and distinguishing favourable from unfavourable patterns. An example statistical distribution of slope and area shape variables is illustrated in Fig. 2(c1), with each dot representing an identified disruption event. An event having small area and steep slope indicates minimal losses of functionality and rapid recovery, respectively, reflecting a favourable ability to handle stressors, and vice versa. A subsystem with a higher proportion of these favourable events demonstrates generally good resilience in handling stressors, whereas a dominance of unfavorable events indicates the opposite.

(2) Annual resilience metrics

Shape variables collected from all disruption events within a year are aggregated to derive annual resilience metrics (e.g., 4Rs), which are normalised within the range of 0–1 (Fig. 2(c2)). For example, a system's annual robustness can be quantified as the mean residual functionality (the magnitude shape variable) across all disruption events, normalised by its normal functionality (threshold). This ratio reflects the system's average ability to maintain performance under stressors during the year. Comparing these metrics enables decision-makers to identify specific weaknesses in subsystem behaviour during a given year and facilitate targeted improvements. For example, using sewer flooded volume as an indicator, a drainage system with low robustness but high rapidity may experience significant flooding yet recover quickly. This may suggest that flooding is caused by intense stormwater inflow rather than insufficient conveyance capacity. Managers could then focus on slowing stormwater entry, through measures such as larger manholes or permeable pavements, rather than expanding main pipe sizes.

Annual resilience metrics also allow inter-subsystem comparison of system behaviour under the same stressors within a year, to understand which specific characteristics are particularly impacted. For example, in a hydrologically wet year, river high-flow robustness may decrease due to elevated flood risks, while water supply redundancy may improve due to increased reservoir availability. These insights would facilitate a holistic understanding of integrated water systems for stakeholders.

(3) Long-term synthesised resilience variation

These resilience metrics are synthesised into a single annual value to represent overall system performance and reveal long-term variations over decades. To mitigate stakeholder subjectivity in weighting (Challenge 6), multiple methods should be tested. For weighted-average synthesis, subjective weights from stakeholders can be complemented by objective weights derived based on the metric statistical properties. For example, entropy methods assign higher weights to resilience metrics with greater sample variations across subsystems, as they may better distinguish the behavioural characteristics and lead to more effective synthesis (Zhu and Liu, 2021). Furthermore, more advanced statistical methods, such as Principal Component Analysis (PCA) and Factor Analysis (FA), could be employed to reduce dimensionality and extract key underlying factors representing overall resilience (Zhu et al., 2025).

The long-term resilience variations provide insights for future strategic subsystem planning. For example, as shown in Fig. 2(c3), Subsystem 1, which exhibits persistently low resilience, should adopt continuous interventions to systematically enhance resilience, such as addressing constantly poor river water quality due to heavy pollution loading. In contrast, Subsystem 2, with overall strong long-term performance, only needs short-term preparations to prevent disruptions in occasional years, such as managing rare extreme rainfall events for a well-designed sewer system. Furthermore, by investigating the decadal average resilience, stakeholders can also identify the critically weak subsystems that need prioritised management and investment, which guides coordinated decision-making for better overall performance.

3.4. Stakeholder engagement for justifying and revising assessments

Finally, all of these results and management insights for individual subsystems should be thoroughly reviewed and discussed via deep engagement of stakeholders, including water companies, regulators, policymakers, and local communities. This aims to justify the reasonability of the results based on stakeholders' knowledge. To facilitate such justification, we propose applying the assessment steps 1–3 to historical periods. This application enables validation by comparing resilience results and empirical evidence (e.g., known substantial historical disruptions) as well as stakeholders' perceptions (e.g., how the subsystem normally behaves). Discrepancies may arise, such as high resilience values during periods of known disruptions or mismatches between trends (e.g., steady resilience levels despite long-term water quality degradation).

Addressing these discrepancies provides insights to refine resilience assessment approaches, particularly in performance indicators, resilience metrics, and synthesis methods that involve subjectivity and arbitrariness (Challenge 4–6). Uninformative indicators and ineffective methods should be identified and replaced with viable alternatives. These revisions should be iteratively tested and reviewed until the setting for the previous three steps (Sections 3.1–3.3) is standardised, with resilience results accepted by stakeholders across all subsystems. This is critical before applying these metrics to design management strategies for future scenarios. Alternatively, machine-learning models could enable more objective parameter evaluation. For example, training models on historical performance data alongside validated disruption events can facilitate threshold derivation, enabling more accurate disruption detection. This approach may accelerate the framework implementation by reducing reliance on iterative refinements. Nevertheless, it depends on the availability of extensive historical data and system knowledge.

4. Application for integrated water resources management

Once validated and approved by stakeholders, this resilience assessment framework can guide the design of management interventions to address diverse stressors in integrated water systems. By incorporating resilience-based insights, the framework complements

conventional IWRM planning approaches. It specifically addresses challenges in management coordination, such as trade-off evaluations, investment prioritisation, and cross-regional scalability. Below, we conceptually illustrate its practical utility through three application scenarios.

4.1. Quantifying and interpreting co-benefits and trade-offs for actionable coordination

Existing research highlights that the complexity of water system processes allows stressors and interventions to propagate, resulting in co-benefits and trade-offs among management objectives (Fig. 3) (Liu et al., 2023a). These effects are often expressed as changes in physical indicators, such as reduced stormwater volume (m^3/s) but increased river nutrient concentrations (mg/l) (Zhang et al., 2021b). Comparing such diverse indicators is challenging due to their different units and physical meanings. The proposed resilience assessment framework standardises these changes into uniform resilience metrics. This enables a direct comparison of co-benefits and trade-offs across subsystems and temporal scales from individual disruption events to long-term cumulative effects.

Comparing changes in synthesised subsystem resilience alone is insufficient for effective coordinated decision-making, as highlighted by Challenge 8. These changes must be unpacked to evaluate the acceptability of trade-offs. A potential solution involves establishing unacceptable resilience levels tailored to each subsystem. Stakeholders can customise these levels onto individual resilience metrics according to specific management objectives, which will enable targeted decision-making. For example, flood managers may prioritise reducing river flow peak damage and thus set strict levels for the robustness metric (Fig. 3). If a trade-off significantly reduces this metric below the level, it is deemed unacceptable. Conversely, if the trade-off can maintain all resilience metrics above the level, the subsystem's performance still remains satisfactory, making the trade-off acceptable. This approach translates resilience changes into actionable criteria aligned with stakeholders' needs, enabling practical coordination among stakeholders.

Such deep stakeholder engagement in resilience assessment in integrated water systems can be operationalised through social science

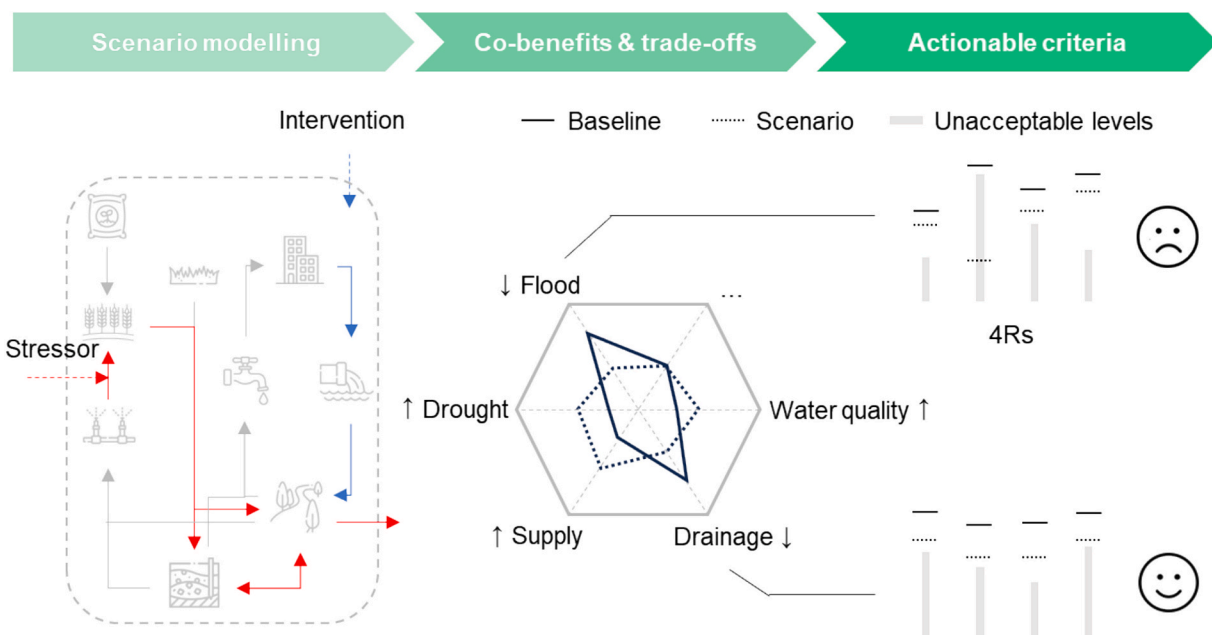


Fig. 3. Application of proposed resilience assessment framework under scenarios of stressors and interventions, for quantifying cobenefits and trade-offs and facilitating actionable decision-making coordination.

methods, such as participatory modeling (Roque et al., 2022) and social network analysis (Manny et al., 2022). These methods help bridge disciplinary divides and enhance knowledge exchange, enabling stakeholders to better understand all the subsystems' responses to stressors and the system-wide impacts of resilience planning decisions. By integrating such methods with the resilience assessment framework, stakeholders can collaboratively establish shared objectives and co-develop management alternatives and scenarios assessment. This fosters consensus and strengthens commitment to sustainable water management for broader system-level resilience benefits.

4.2. Evaluate cost-effectiveness of resilience planning for future decision-making

Given the incomplete knowledge of future stressors, planning for resilient water systems aligns closely with decision-making under deep uncertainties (DMDU) (Mijic et al., 2024). DMDU studies on water subsystems have demonstrated widely-existing resilience-cost trade-offs, where higher resilience typically requires greater investment (Groves et al., 2019; Pachos et al., 2022). However, suboptimal outcomes have often been reported: oversized planning leads to unnecessary costs when stressors are milder than anticipated, while undersized planning fails to address actual stressors (Cook et al., 2020; Robinson & Herman, 2019).

With the stakeholder-specified unacceptable resilience levels, applying the proposed assessment framework can examine the cost-effectiveness of planning decisions for the whole integrated water

systems. For instance, as illustrated in Fig. 4, during the first planning period, projected increases in precipitation reduce resilience in subsystems like flood and urban drainage below unacceptable levels. This necessitates investments in interventions such as levees, floodplains, and urban sewer expansion. The actual conditions match projections, so that these investments are cost-effective and yield satisfactory resilience outcomes.

In the second planning period, while projections predict wetter conditions requiring continued investment in flood-related systems, actual climate conditions may turn drier. This mismatch can render the investments in this period unnecessary and lead to resilience in water supply, river low flows and water quality falling below the unacceptable levels. This unsatisfactory outcome is likely, as global circulation models (GCMs), commonly used for long-term planning, often exhibit low accuracy in predicting decadal climate variability (Nissan et al., 2019). Further modelling experiments can identify additional investments needed to restore resilience in those underperforming subsystems. By periodically assessing deviations from unacceptable resilience levels and estimating supplementary investments, applying the framework in DMDU can promptly prevent repeated misallocations and enhance system-wide resilience in a balanced manner. Nevertheless, the validity of the results depends on the model's accuracy within the given decision context, highlighting the importance of quantifying simulation biases in the evaluation of suboptimal outcomes.

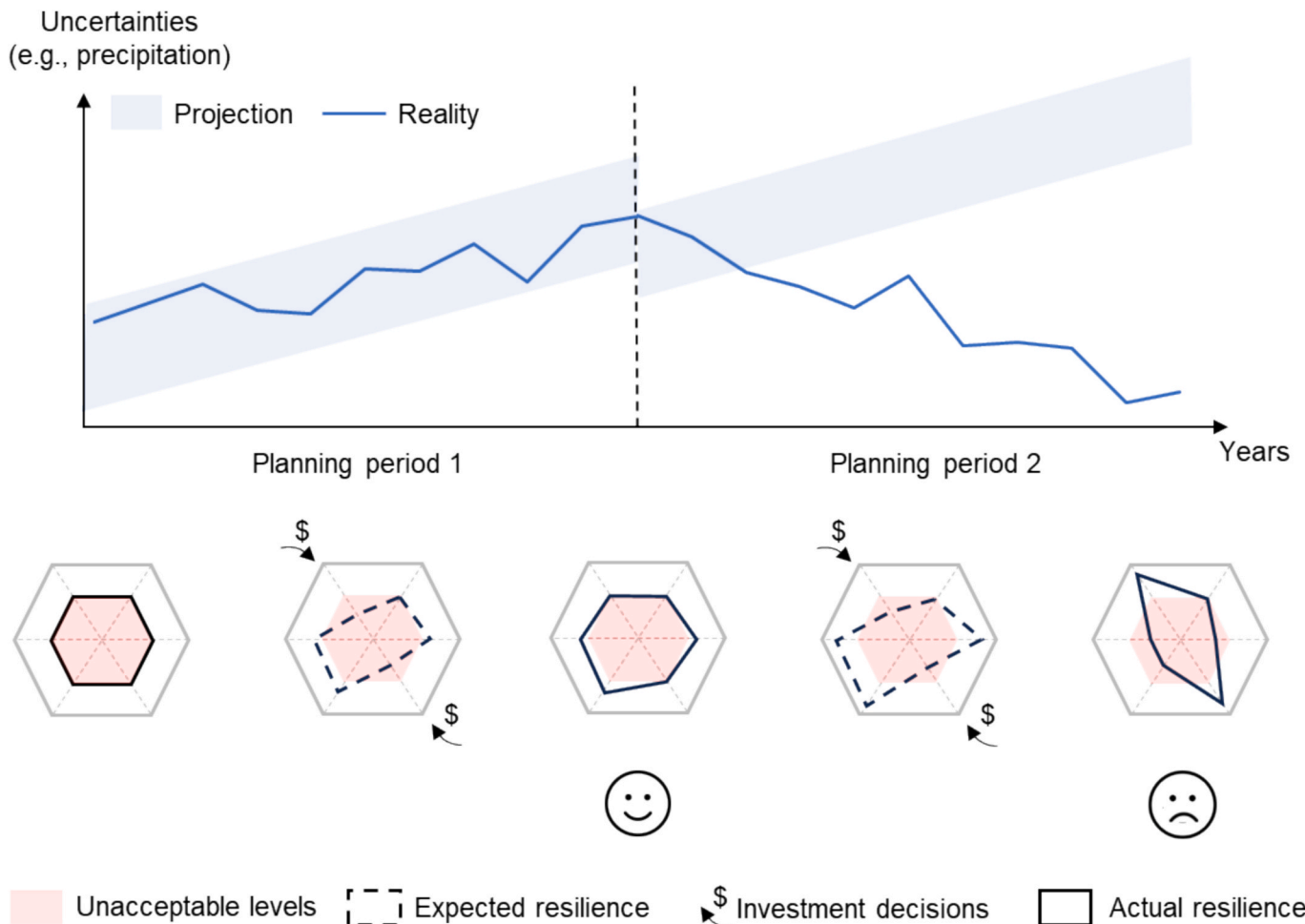


Fig. 4. An illustrative DMDU scenario for using the resilience assessment framework to evaluate the cost-effectiveness of planning decisions in integrated water systems.

4.3. Benchmarking analysis between resilience profiles for global knowledge sharing

Applying the framework onto large regional systems can reveal catchment resilience profiles and their variations. Such comparative analysis helps identify how catchment system characteristics and key stressors influence resilience. For example, in the River Lee catchment in the UK (Fig. 5(a)), chalk streams with high recharge and dominant subsurface processes may exhibit strong resilience to mitigate extreme dry and wet climate conditions, whereas catchments with impermeable land cover have rapid runoff routing, which increases flood and drought risks. Similarly, fertilisers and manure in rural catchments are primary stressors driving low nitrogen resilience, while urban catchments are more affected by wastewater effluents leading to low phosphorus resilience (Liu et al., 2021). Such insights support the design of targeted interventions to address resilience challenges in specific regions.

With the increasing adoption of integrated water resilience assessment and planning, this information can be compiled into a global database (Fig. 5(b)). The database could include catchment system and stressor characteristics, detailed assessment approaches, resilience results, planned solutions, and cost-effectiveness data. Leveraging machine learning techniques, a platform could be developed as a 'handbook' to assist catchment managers and planners. Users could input available data regarding catchment characteristics and receive resilience predictions, recommended interventions, and insights from comparative cases. This approach is particularly valuable for resilience diagnosis and planning in developing countries or regions with limited data and modelling resources. Such a platform supports the Sustainable Development Goals (SDGs) and the United Nations Water Initiative to promote resilient water systems worldwide.

5. Conclusions

This review explores the applicability of performance-based resilience assessment in integrated water systems by examining existing studies across urban, rural and natural subsystems. Key elements of the assessment, including performance indicators, thresholds, and resilience metrics, were analysed to identify eight challenges inherent to integrated water systems. These challenges primarily focus on achieving consistent resilience assessment results across subsystems, accommodating stakeholders' specific management needs, and enhancing interpretation for supporting coordinated decision-making.

To explore overcoming these challenges, a potential resilience assessment framework is proposed for integrated water systems. This framework advances the existing isolated subsystem assessment by incorporating (1) unified metrics to enable cross-subsystem intercomparison; (2) integrated modelling to capture cascading disruptions from subsystem interdependencies; (3) a bottom-up synthesis to reveal short- and long-term system behaviour, and (4) stakeholder-engaged validation and iterative refinement to yield consensus-grounded resilience insights.

To further demonstrate the framework's utility for integrated water resources management, we then design three application scenarios: (1) quantifying co-benefits and trade-offs at a unified scale, (2) evaluating cost-effectiveness of planning decisions, and (3) guiding regional planning based on catchment characteristics. These scenarios extend conventional IWRM by integrating resilience dynamics into management strategy design, offering opportunities to address the difficulties in current decision-making coordination. Future research could validate these scenarios through case studies, generating evidence on the operational benefits of resilience-informed IWRM.

Despite its strengths, this framework faces practical challenges in real-world applications. Current models do not yet fully represent the nested complexity of integrated water systems, creating uncertainties in

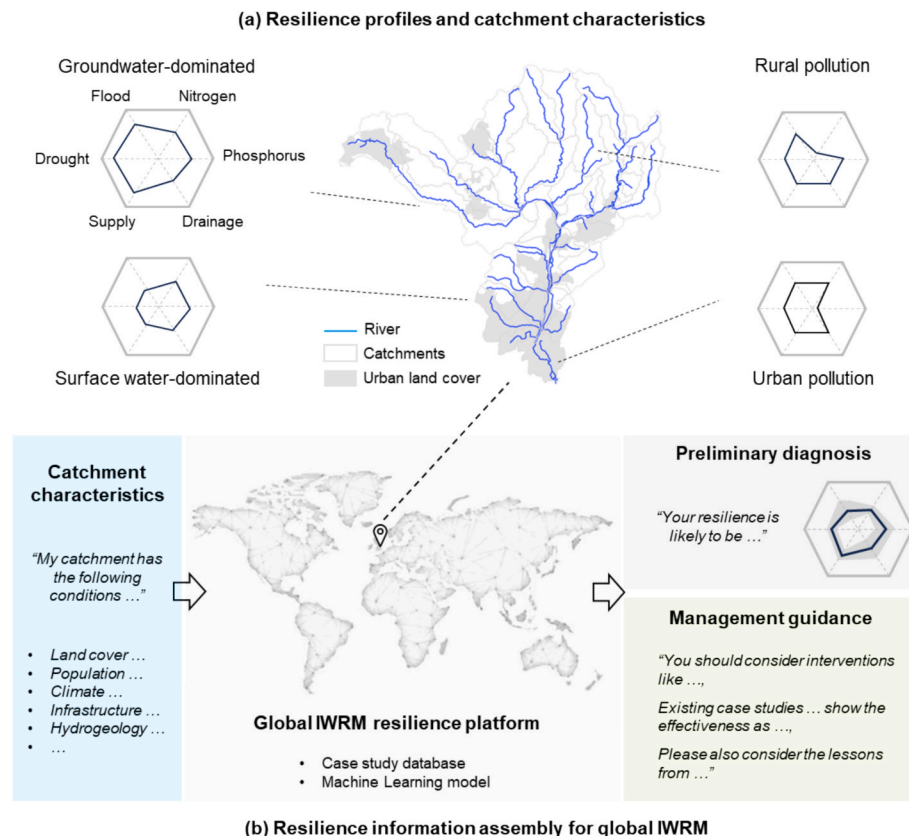


Fig. 5. Create resilience profiles within large regional systems (a) and assembly case studies onto an information platform for global IWRM (b).

model structures (i.e., mathematical representations of processes) and parameters. Due to the framework's reliance on integrated modelling, such uncertainties can propagate into resilience results, which could distort disruption events identification and hinder subsequent decision-making. Managing such uncertainties requires rigorous model validation and sensitivity analysis, particularly for internal processes critical to performance indicator evaluation. However, such efforts demand substantial data acquisition and computational resources, which are often limited in developing regions. Furthermore, effective framework implementation necessitates stakeholder collaboration. Currently, integrated water management platforms or institutions capable of coordinating such assessments at a catchment scale are rare. This framework may require restructuring existing institutions and developing new water governance regimes to better support integrated resilience planning.

CRedit authorship contribution statement

Leyang Liu: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ana Mijic:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jhydrol.2025.134042>.

Data availability

The reviewed papers and the relevant information have been listed in the [Supplementary Materials](#).

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