Smart Water Reliability: How Digitalisation Is Redistributing Reliability Work in Water Systems.

Jennifer R. Ayres[1a], **Kate Bullen**[b], **Ian May**[c].

[a] Engineering Consultant, Adelaide, South Australia.

[b]MWH Treatment, Spring Lodge, 172 Chester Road, Helsby, Cheshire, England, WA6 0AR

[c]Cranfield University, College Rd, Cranfield, Wharley End, Bedford, United Kingdom, MK43 0AL

[1]Corresponding author: ayresjeni@gmail.com
ORCID IDs [1] 0000-0002-4538-6512;

Abstract

The reliability of water systems is undergoing a fundamental transformation as digitalisation, climate pressures, and regulatory scrutiny reshape how performance is sustained in practice. Traditional milestone-based assurance—where reliability was validated at commissioning and assumed stable thereafter—no longer reflects the operational realities of smart, data-rich infrastructure. This paper introduces Smart Water Reliability (SWR) as a framing concept for understanding how reliability is now produced through the continuous interaction of digital visibility, professional judgement, and organisational adaptation. Drawing on long-term industry observation across commissioning and operational contexts, the paper identifies five competence patterns that illustrate this shift: the erosion of sensory knowledge, signal saturation and attention triage, the commissioning blind spot, asymmetric visibility, and compliance by proxy. These patterns reveal how reliability work is being redistributed across sociotechnical boundaries, often in ways that remain invisible within existing engineering frameworks. By articulating these emerging forms of competence, SWR provides a conceptual anchor for industry and research communities seeking to understand and respond to the changing demands of reliability practice in digitally mediated water systems. The paper concludes by outlining implications for training, governance, and professional formation, positioning reliability as a dynamic, negotiated process rather than a static technical attribute.

Keywords: Smart water systems; Reliability engineering; Digital infrastructure; Commissioning; Professional competence; Sociotechnical systems

1. Introduction

Reliability in water systems is no longer a matter of "build it once and trust it."(ISO, 2024). What was once assured through design adequacy and commissioning milestones is now continuously renegotiated amid digitalisation, climate pressures, and regulatory scrutiny.

This paper introduces Smart Water Reliability (SWR) as a framing concept for understanding these industry changes. It identifies five competence gaps that illustrate how reliability work is being redistributed in practice.

For much of the twentieth century, reliability in water engineering was understood as a function of design adequacy, construction quality, and periodic maintenance (Perrow, 2011; Reason, 2016). This understanding reflects a classical engineering view of reliability as a property designed into systems and periodically restored through maintenance, rather than something actively produced during everyday operation.

Such milestone-based assurance implicitly assumed relatively stable operating conditions and a clear separation between project delivery and ongoing operational judgement. This milestone-based assurance aligned with relatively stable system conditions, slower rates of change, and organisational structures in which responsibility for performance was clearly segmented across lifecycle stages.

That framing is no longer sufficient. The reliability of water systems is undergoing a profound transformation as digitalisation, sustainability pressures, and increasingly complex system interdependencies reshape how performance is understood and sustained in practice. For decades, commissioning and operational assurance were treated as discrete technical events: systems were validated against design specifications, handed over, and assumed reliable until failure or maintenance intervened. This event-based framing of commissioning aligns with traditional reliability engineering approaches that emphasise design compliance and initial validation rather than ongoing operational performance (Reason, 2016).

Contemporary water infrastructure now operates under conditions in which such assumptions are increasingly difficult to maintain. Studies of complex sociotechnical systems show that reliability degrades when organisational structures and practices fail to adapt to increasing system complexity and uncertainty (Perrow, 2011).

Across the water industry, intelligent monitoring technologies generate continuous streams of data, shifting reliability from a static handover milestone to a dynamic, ongoing process. Sector syntheses of data-driven urban water management emphasise that this shift is driven not by instrumentation alone, but by growing dependence on analytics, interpretation, and organisational response to sustain performance over time (Eggimann et al., 2017).

Climate change and evolving regulatory demands have introduced new lifecycle pressures, requiring systems to adapt amid uncertainty and variability. From a systems-safety perspective, managing reliability under such conditions constitutes a dynamic control problem, in which stable short-term performance can mask shifting boundaries and accumulating risk (Rasmussen, 1997).

At the same time, the integration of hydroinformatics, automation, and advanced analytics has blurred the boundary between technical validation and organisational judgement.

Sociotechnical systems research emphasises that technological performance and organisational decision-making are inseparable in complex operational environments (Hollnagel et al., 2006). Reliability is no longer a matter of "checking the box" at commissioning; it is negotiated continuously at the intersection of digital visibility, operational practice, and professional interpretation.

This shift away from checklist validation is occurring alongside increasingly variable environmental conditions and tightening regulatory expectations, both of which place sustained pressure on system performance and heighten reliance on continuous monitoring and adaptation.

What has received less attention is how these new approaches reshape the work required to sustain reliability in practice. Empirical studies of operational work consistently show that sustaining system performance depends on informal coordination, local judgement, and adaptive responses that are rarely captured in formal reliability models (Dekker, 2017). As systems become more instrumented and performance is increasingly represented through dashboards and indicators, some aspects of reliability work become more visible, while others recede from view.

While data representations foreground measurable indicators, they can simultaneously obscure the interpretive and coordinative work required to translate signals into timely operational action. Activities such as sense-making, coordination, prioritisation, and judgement do not disappear in smart systems; instead, they become harder to articulate, justify, and recognise. These activities are consistent with scholarship on 'invisible work', which shows that essential coordination and sustaining labour often disappear from formal accounts precisely when systems appear to function smoothly (Star and Strauss, 1999).

Existing reliability framings, which privilege technical robustness and measurable outcomes, struggle to account for this redistribution of effort and responsibility. This limitation reflects a broader tendency within safety and reliability management to privilege formalised controls over the situated practices through which reliability is actually achieved (Hopkins, 2012).

International standards such as ISO 55000 and the WHO's Water Safety Plans increasingly frame reliability as a lifecycle obligation sustained through continual monitoring rather than one-time certification. This regulatory shift toward ongoing adaptation reinforces industry changes driven by digital visibility and climate pressures.

Together, these shifts challenge traditional assumptions about where reliability resides and how it is assured, raising fundamental questions about the forms of work now required to sustain reliable performance in smart water systems. Addressing these questions requires moving beyond purely technical accounts of reliability to examine how digital visibility, organisational arrangements, and professional judgement interact in practice.

This paper introduces **Smart Water Reliability** as a framing concept for understanding these industry changes. It is not proposed as a new technical standard, prescriptive model, or performance metric. Rather, SWR enables engineers and researchers to recognise and articulate forms of reliability work that existing frameworks overlook. Instead, it offers a lens for examining how reliability is produced and sustained in digitally mediated water systems, where performance depends not only on assets and algorithms, but on ongoing professional judgement, coordination, and adaptation. The focus is explicitly industry-led: to capture how

reliability practices are evolving, why engineers must adapt, and what forms of competence are becoming increasingly central in this new operational environment.

This paper contributes to both industry practice and scholarly debate by introducing Smart Water Reliability (SWR) as a framing concept for understanding reliability in digitally mediated water systems. Unlike existing standards and guidelines that emphasise lifecycle assurance or technical robustness, SWR foregrounds the redistribution of reliability work across digital visibility, professional judgement, and organisational adaptation. Specifically, the paper identifies five competence gaps that illustrate how reliability is now sustained in practice: (1) the erosion of sensory knowledge in digital environments, (2) signal saturation and attention triage, (3) the commissioning blind spot where validation occurs without interpretive understanding, (4) asymmetric visibility that separates data from operational context, and (5) compliance by proxy. By articulating these gaps, the paper positions SWR as a conceptual anchor for future research and industry adaptation, offering a lens through which reliability can be understood not as a static certification but as a dynamic, negotiated process.

These five patterns, illustrated in Figure 1, emerge from the continuous negotiation between digital visibility and professional judgment that defines Smart Water Reliability.

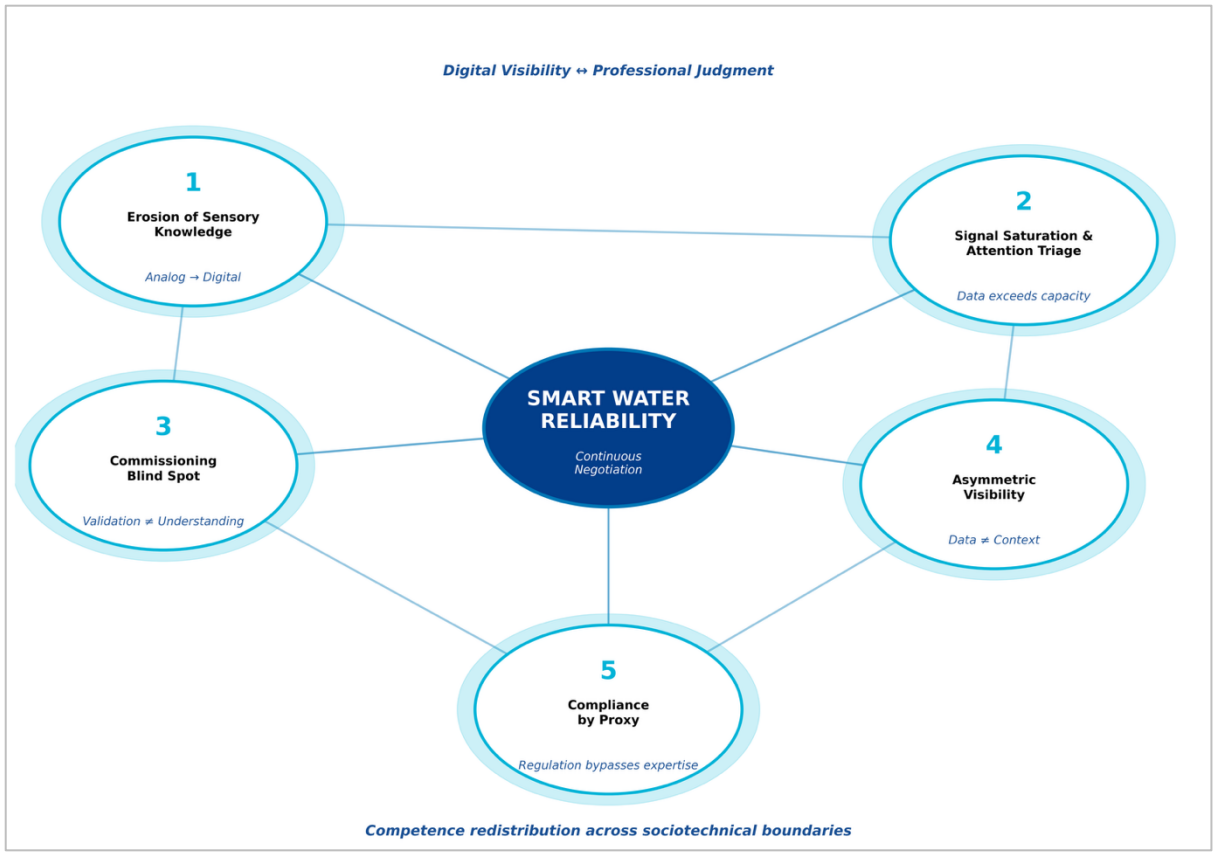

Figure 1: The Five Competence Patterns of Smart Water Reliability. SWR emerges from the continuous negotiation between digital visibility and professional judgment. Five patterns illustrate how reliability work is being redistributed across sociotechnical boundaries: (1) Erosion of sensory knowledge as analog expertise gives way to digital monitoring, (2) Signal saturation as data volume exceeds attention capacity, (3) Commissioning blind spot where validation occurs without interpretive understanding, (4) Asymmetric visibility where data and context are separated, and (5) Compliance by proxy where regulatory assurance bypasses operational expertise.

Section 2. The Changing Landscape of Reliability

Water systems no longer sustain reliability through static assurance at commissioning milestones (Pahl-Wostl, 2006). Instead, it is continuously produced and renegotiated as systems operate under dynamic conditions. Intelligent monitoring technologies have made performance more visible, but visibility does not equate to certainty. Dashboards and indicators provide streams of data that must be interpreted, contextualised, and acted upon, often under conditions of ambiguity (Endsley, 1995).

At the same time, external pressures are reshaping the reliability landscape. Infrastructure governance research shows that regulatory, climatic, and societal pressures increasingly interact, compounding uncertainty rather than acting as isolated drivers (Romano and Akhmouch, 2019). Climate variability introduces new forms of stress on water systems, from extreme events to gradual shifts in baseline conditions (Brown et al., 2009). Regulatory frameworks are evolving to demand greater transparency, accountability, and sustainability, placing organisations under constant scrutiny. These pressures mean that reliability can no longer be assumed to persist once commissioning is complete; it must be actively sustained through ongoing adaptation.

The integration of hydroinformatics, automation, and advanced analytics has further complicated the picture (Makropoulos and Butler, 2010). Technical validation is increasingly inseparable from organisational judgement, as algorithms and models generate outputs that require professional interpretation. Reliability now resides at the intersection of digital visibility and human decision-making, where neither assets nor data alone can guarantee performance.

2.1 Temporal mismatches and integration complexity

Temporal and technical mismatches between infrastructure development cycles and the pace of technological change compound the challenges of sustaining reliability in smart water systems. Water infrastructure projects typically operate on multi-year timelines: design specifications are finalised, procurement occurs, construction proceeds, and commissioning follows—a process that may span three to five years or longer for major projects. Research on large infrastructure projects shows that long delivery timelines systematically amplify risk where technology, scope, and operating contexts evolve faster than project governance structures (Flyvbjerg, 2014). During this period, sensor technologies, data platforms, communication protocols, and software architectures continue to evolve, often on twelve to eighteen-month cycles.

This temporal gap can create complications that may not become apparent until commissioning. Equipment specified during design must integrate with existing infrastructure—legacy SCADA systems, established data protocols, aging network architecture—that may predate the new technology by a decade or more. Compatibility issues that were not foreseeable during design can emerge when systems are connected: communication protocols may not align, data formats may require translation layers that were not budgeted, or interface assumptions embedded in new equipment may not match the operational logic of legacy systems (Love et al., 2016).

The expertise required to resolve such integration challenges is often specialised and costly. Engineers who understand both contemporary smart technologies and the particular legacy systems into which they must be integrated represent a scarce resource. When integration difficulties emerge during commissioning—precisely when project timelines are most constrained—the availability of specialists capable of diagnosing and resolving compatibility issues may become a critical bottleneck. This can place projects in difficult positions: delay commissioning to secure appropriate expertise, attempt workarounds that may compromise functionality, or proceed with partial integration and accept reduced system capability (Bach et al., 2014; Mounce et al., 2003; Poch et al., 2004).

Contractual structures can further complicate adaptation. Procurement specifications typically require the installation of equipment identified during design, providing cost certainty and project stability. However, this may mean that the equipment ultimately installed reflects technological generations or interface designs that have evolved during the project timeline. In contrast, integration assumptions made during design may not fully align with the systems ultimately deployed. The result can be a situation where engineers navigate unforeseen technical challenges during commissioning without the time, resources, or contractual flexibility to address them systematically.

These mismatches are not failures of planning; they reflect the inherent difficulty of aligning long infrastructure development cycles with rapid technological evolution. Nonetheless, they can create hidden costs and risks: integration challenges can absorb engineering effort that was budgeted for validation and handover, equipment may operate with reduced functionality if full integration cannot be achieved within available resources, and operational staff may inherit systems whose performance or interfaces differ from what training and documentation anticipated. The temporal and technical gaps between design intent and operational reality become challenges that commissioning engineers must navigate through adaptation and improvisation—work that is often neither recognised nor resourced as distinct professional competence.

2.2 Resource constraints and operational dependencies

The structural separation of capital and operational budgets further constrains the ability to sustain system reliability. Asset-management research highlights this separation as a persistent source of reliability gaps, particularly where operational capability is expected to absorb the downstream consequences of capital investment decisions (Hodkiewicz, 2015). Smart monitoring infrastructure is typically funded through capital expenditure: sensors, networks, SCADA upgrades, and dashboards represent tangible assets that can be justified as discrete investments. The ongoing resources required to sustain reliable performance—training, specialist support, coordination capacity, and extended commissioning engagement—fall under operational budgets, where they compete with immediate operational demands and may be subject to cost-containment pressures.

This budgetary structure can create tension between infrastructure capability and operational capacity. Sophisticated digital systems may be installed and commissioned to technical specifications, yet the organisational resources required to interpret outputs, coordinate responses, and maintain systems over time may not be allocated in proportion. Operational budgets may face pressure to minimise recurring costs, even as the infrastructure deployed

creates new dependencies on specialist expertise, vendor support, or coordination mechanisms that require sustained resourcing.

Vendor dependencies for maintenance and servicing can further complicate operational capacity (Gao et al., 2023). Some smart technologies require certified specialists for calibration, servicing, or troubleshooting, reflecting the technical complexity of contemporary instrumentation and the importance of maintaining warranty coverage where specialist availability is limited—whether due to geographical constraints, certification requirements, or market capacity—operational teams may face delays in addressing equipment issues that affect data reliability or compliance monitoring. In contexts where operational budgets do not accommodate premium service costs, standard service timelines may introduce gaps between when problems are identified and when they can be resolved, potentially affecting performance assurance during interim periods.

These resource and dependency patterns do not reflect organisational failure; they emerge from the interaction of infrastructure investment structures, market dynamics for specialised technical services, and the operational realities of managing increasingly complex technological systems within constrained budgets. Nonetheless, they shape the conditions under which reliability must be sustained, introducing challenges that extend beyond technical performance to encompass resource availability, coordination capacity, and organisational adaptation.

2.3 Unintended consequences of enhanced visibility

Smart monitoring infrastructure is typically justified through efficiency gains and early problem detection, yet enhanced visibility can reveal challenges that complicate both financial planning and operational security. Research on risk management and performance transparency shows that enhanced visibility can also expose latent liabilities and create accountability pressures that organisations are not structurally prepared to manage (Power, 2007). Continuous monitoring may detect infrastructure degradation that was not apparent through periodic manual inspection: slow leaks in concrete structures, gradual asset deterioration, or system inefficiencies that were operationally tolerable when invisible but become documented liabilities once quantified. The detection of such issues—particularly when they intersect with compliance or safety obligations—can trigger unplanned capital expenditure requirements that were not anticipated in infrastructure investment planning.

The revelation of previously unknown infrastructure deficiencies through smart monitoring creates a paradox: systems intended to enable proactive management and cost savings may instead expose expensive problems that require immediate attention. Organisations may face difficult decisions about whether to address newly detected issues that were operationally tolerable when undocumented, or to defer interventions despite now having evidence of system degradation. This tension between operational visibility and financial capacity reflects the broader challenge of aligning digital infrastructure capabilities with organisational resources.

Physical security considerations may also emerge unexpectedly. The deployment of smart monitoring equipment—particularly sensors, communication infrastructure, and power cables at remote or unmanned sites—can create new vulnerabilities to theft and vandalism. Copper

cabling used for power and data transmission is a target for theft in some operational contexts, potentially resulting not only in equipment loss but also in damage to surrounding infrastructure during extraction attempts. The costs of securing remote monitoring infrastructure, replacing damaged equipment, and maintaining system integrity against theft or vandalism may not be fully accounted for in project planning, creating ongoing operational expenses that were not anticipated during initial business case development.

These unintended consequences do not invalidate the value of smart monitoring; instead, they illustrate that enhanced visibility and digital infrastructure bring complexities that extend beyond technical performance to encompass financial planning, risk management, and operational security. The full cost of transitioning to smart water systems includes not only equipment installation but also the organisational capacity to respond to what monitoring reveals and to protect the infrastructure that enables visibility.

2.4 Regulatory visibility and infrastructure accountability

The transition to smart water systems represents not only a technical transformation but also a shift in regulatory and organisational accountability. Traditional monitoring regimes—characterised by periodic sampling, manual inspection, and threshold-based compliance reporting—provided operational flexibility by creating temporal and spatial gaps in visibility. System performance that fell between monitoring intervals, infrastructure degradation that progressed gradually between inspections, or localised failures that occurred outside sampling locations could remain undocumented and therefore did not trigger formal obligations to intervene or report.

This information structure was not necessarily designed to obscure performance, but it did create a form of organisational discretion: problems that were not formally documented did not require formal responses. In regulatory contexts where utilities face financial penalties for documented compliance breaches or public scrutiny for acknowledged infrastructure failures, this discretion may have functioned as a buffer, allowing organisations to manage deteriorating infrastructure through operational adjustment rather than capital investment, and to address failures reactively rather than proactively documenting risk.

Smart monitoring infrastructure fundamentally disrupts this equilibrium. Continuous data streams, automated reporting to regulators, and digital records that create permanent documentation transform previously discretionary knowledge into formal evidence. A slow leak that would have gone undetected during quarterly inspections is quantified as a daily flow loss. Intermittent water-quality exceedances that may have fallen between sampling events are now captured in continuous monitoring data. Infrastructure degradation that could be managed informally as "something to watch" becomes documented trend data that may trigger regulatory inquiries about why intervention was not pursued earlier.

For utilities operating under performance-based regulation with financial penalties for documented failures, or in contexts of public scepticism about infrastructure investment priorities, this shift from discretionary awareness to documented evidence can create significant challenges. Organisations may find themselves facing accountability for system conditions that were previously tolerable precisely because they were not comprehensively monitored. The business case for smart monitoring—early detection enables cost-effective

intervention—assumes that organisations have both the resources and the regulatory flexibility to respond to what monitoring reveals. Where these conditions do not hold, enhanced visibility can expose gaps between system performance and regulatory expectations that were manageable when monitoring was less comprehensive.

This dynamic has become particularly visible across diverse jurisdictions. In the United Kingdom, public scrutiny of water utility performance has intensified as smart monitoring reveals discharge patterns and system behaviours that were not comprehensively documented under legacy monitoring regimes. In the United States, infrastructure accountability debates—from contamination concerns in ageing distribution systems to treatment plant performance verification—reflect tensions between enhanced monitoring capabilities and the financial capacity to address what visibility exposes. In Australia, urban water utilities navigating drought resilience and regulatory compliance face similar challenges, as continuous monitoring documents system conditions that periodic sampling did not capture. While regulatory structures, ownership models, and performance frameworks differ across these contexts, the typical pattern is consistent: enhanced monitoring transforms previously discretionary knowledge into documented evidence, creating accountability pressures that organisational and financial structures were not designed to accommodate.

The introduction of smart monitoring into contexts where public infrastructure investment has not kept pace with system ageing does not create infrastructure problems—those problems existed—but it does remove the information asymmetry that previously allowed their management to remain organizationally discretionary. The result is an accountability crisis: utilities must now respond to documented evidence of conditions that were previously known only informally, if at all, and do so within financial and regulatory structures that were not designed for comprehensive, continuous monitoring.

The implications extend beyond individual utilities to industry-wide questions about how the transition to smart infrastructure should be governed. If enhanced monitoring reveals the actual state of ageing infrastructure—and that state is worse than intermittent monitoring suggested—how should regulatory frameworks balance accountability for current conditions against recognition that previous monitoring regimes did not require such comprehensive documentation? How should financial planning accommodate the capital requirements that comprehensive monitoring may expose? And how should organisations navigate the tension between operational transparency, which smart systems enable, and organisational liability, which documented evidence can create?

These questions do not have simple answers, but they must be acknowledged as central to the industry transformation that smart water systems represent. Reliability in this context is not only technical assurance but also organisational and regulatory adaptation to a new information environment where discretionary knowledge becomes documented evidence, and where visibility itself becomes a form of accountability.

3. Why Engineers Must Adapt

The changing reliability landscape places new demands on professional practice, but the specific competences now required are often misrecognized or undervalued. Five patterns, common across water infrastructure projects, illustrate the competence gap emerging between

traditional practice and smart water realities. The patterns presented here derive from long-term industry observation across multiple commissioning and operational contexts.

3.1 The erosion of sensory knowledge in digital environments

Legacy systems relied partly on sensory knowledge to sustain reliability: experienced operators knew a pump "sounded wrong" before instruments indicated bearing failure, recognised treatment quality from water colour and clarity, and felt pressure anomalies through valve resistance. This tacit competence, accumulated over years of embodied practice, often proved more reliable than intermittent manual measurements or ageing instrumentation (Eraut , 2004; Polanyi, 2009)

Smart systems promise to replace this with continuous sensor streams and algorithmic monitoring—yet the transition is far from seamless. Across operational sites, a persistent pattern emerges: experienced operators continue to rely on sensory judgment, often distrusting sensor readings that contradict what they observe directly. Newer staff, lacking years of embodied familiarity with the system, inherit this distrust without inheriting the sensory baseline that justified it. The result is a generational transfer crisis: tacit knowledge that once served as reliability assurance is disappearing, but it is not being replaced by confident engagement with digital systems. Instead, both experienced and early-career engineers exist in a state of suspension—uncertain whether to trust instruments or instinct, and increasingly lacking fluency in either.

This erosion manifests in operational practice through what might be called 'data-deference': operators encountering physical symptoms—a pump vibrating irregularly, an unusual odor from a treatment process, unexpected temperature variation—are instructed to await digital confirmation before intervening. The rationale is efficiency: investigate only when sensors trigger alerts, reducing unnecessary site visits and labour costs. The consequence is dual: potential failures progress undetected while physical cues remain below algorithmic thresholds, and operators progressively lose confidence in their capacity to interpret sensory information without digital validation. Over time, the tacit knowledge required to diagnose incipient failure states—the subtle differences between normal operational variation and emerging dysfunction—atrophies from disuse and institutional delegitimating (Rasmussen, 1997).

This is not resistance to technology; it is a rational response to inadequate transition support. When an operator with twenty years of system knowledge observes that "something feels off," but sensors indicate regular operation, whose judgment should prevail? Current reliability frameworks do not guide this negotiation. Engineers are left to navigate these tensions individually, often defaulting to whichever knowledge source aligns with established authority structures rather than operational reality.

3.2 Signal Saturation and Attention Triage

A frequently encountered pattern in data-rich operational environments is signal saturation, in which increasing volumes of data-based indicators compete for limited attention. As

information density increases, operational staff must continuously triage signals, distinguishing between routine variability and conditions warranting concern (Endsley, 1995). This process is not discretionary; it is a necessary response to environments in which more information is available than can be meaningfully attended to at any given time.

Over time, repeated signals that do not lead to immediate or visible consequences may be tacitly deprioritised. Deviation can become normalised, not through negligence or complacency, but through sustained exposure to indicators that appear operationally inconsequential (Dekker, 2017). In such contexts, selective attention serves as a coping strategy that enables work to continue under cognitive and temporal constraints. What is filtered out is not necessarily unimportant, but what cannot be practically accommodated within existing attention budgets.

In practice, the absence of alarms or formal escalations is often interpreted as confirmation that conditions are acceptable. Where workloads are high and attention stretched, silence itself can become a proxy for safety. Signals that do not demand explicit response may therefore receive diminishing scrutiny, even when they indicate gradual or cumulative change. Over time, the lack of interruption becomes reassuring, reinforcing the assumption that no action is required unless prompted by an overt alert or escalation.

Risk emerges in these circumstances not because information is unavailable, but because it competes unsuccessfully for attention in environments where explicit prompts carry disproportionate weight. Early indicators may remain visible within the data environment yet fail to disrupt routine practice until tolerance margins are approached or exceeded.

3.3 The commissioning blind spot: validation without understanding

Commissioning practice treats validation as technical confirmation: sensors are installed correctly, calibrated to specification, and generating plausible data streams (Hopkins, 2012). Sign-off is granted, the system is handed over, and reliability is assumed. Yet this framing systematically overlooks a critical dimension: whether operational staff understand what sensor readings mean, when readings warrant action, and how to interpret anomalies.

This blind spot is not limited to others. Commissioning engineers, including the author, routinely assume that if they understand system behaviour, operational staff will too. The assumption is rarely tested. Handover documentation may include sensor specifications and calibration certificates, but seldom includes interpretive guidance: what constitutes normal variation versus concerning drift? When do multiple "minor" anomalies signal systemic issues? How should algorithmic alerts be weighed against direct observation?

Six months after handover, the consequences become visible. Operators either ignore sensor outputs—because the readings do not align with operational intuition and no reconciliation framework exists—or they act on readings without interpretive context, potentially intervening inappropriately or missing genuine system degradation. In both cases, reliability is compromised, not by technical failure but by the absence of shared competence in interpreting digital visibility (Hollnagel et al., 2006).

This is not a training failure in the conventional sense. Operators may have attended vendor workshops on using monitoring interfaces yet still lack the contextual knowledge to judge when data streams are trustworthy. Commissioning engineers validated that sensors work, but not whether the sociotechnical system—sensors plus human interpretation plus organisational response protocols—functions reliably under operational conditions.

3.4 Asymmetric visibility: dashboards in exile

These systems generate unprecedented data streams, yet visibility is often asymmetrically distributed. Dashboards and performance indicators reside in management offices, accessible to asset planners and strategic decision-makers but not to on-site operational staff. Meanwhile, engineers and operators—those with embodied system knowledge and the interpretive competence to judge whether anomalies matter—remain "not privy to the reports until there is an issue, and it's often too late."

This visibility asymmetry extends beyond compliance to operational decision-making. Site operators working with ageing infrastructure often encounter early warning signs—unusual pump noise, unexpected vibration, odour changes, temperature variations—that indicate incipient failure but have not yet crossed algorithmic thresholds. In previous operational cultures, such observations would trigger immediate investigation. In data-mediated environments, operators are increasingly instructed to defer action until digital systems confirm the problem, a practice justified as a cost-efficient way to allocate resources. The immediate consequence is that potential failures progress further before intervention. Still, the long-term effect is more insidious: operators lose both the tacit knowledge required to interpret physical symptoms and the organisational legitimacy to act on sensory expertise that contradicts dashboard indicators. The resulting competence erosion is rarely visible in performance metrics until significant failures occur. At this point, investigations reveal that site personnel "noticed something wrong" but were instructed—or had learned through organisational culture—not to trust their judgement over data (Star and Strauss, 1999).

This inversion creates a reliability paradox: the people best positioned to interpret data do not see it until corrective action windows have closed. By the time operational staff are consulted, systems have already transitioned from minor drift (detectable in trend data) to acute failure (requiring emergency intervention). Asset managers reviewing dashboards may observe indicators trending unfavourably but lack the operational context to assess whether intervention is urgent, whether the variation is normal for seasonal conditions, or whether the alerts represent genuine risk versus calibration artefacts.

The consequence is not merely inefficiency; it is a fundamental weakening of reliability assurance (Power, 2007). Continuous monitoring was intended to enable proactive intervention and catch system degradation early. Instead, it creates a situation in which some people have data without context, while others have context without data. Reliability, which depends on integrating both, is systematically undermined.

3.5 Compliance by proxy: regulatory blindness on site

The asymmetry extends beyond operational dashboards to regulatory and licensing compliance. Instrument readings that determine whether treatment meets discharge standards, whether water quality satisfies health regulations, or whether environmental limits are observed are increasingly bypassed by site personnel entirely. Data streams flow directly to clients, regulatory agencies, or head-office compliance teams—often accessed by non-technical staff responsible for reporting but lacking operational context to interpret what the readings signify.

Site engineers and operators are not entirely blind: acute breaches trigger alarms, enabling immediate response to exceedances that threaten public health or environmental harm. This reactive capacity is critical and generally functions as designed. What remains invisible, however, are the cumulative patterns that determine regulatory compliance: the 95th percentile calculations, the rolling averages over quarterly or annual periods, the frequency distributions that distinguish occasional variation from systemic drift. These metrics are calculated and monitored at the head office, often by personnel responsible for regulatory reporting but with limited operational familiarity with the systems that generate the data.

This creates a deceptive reliability condition. Engineers on site believe they are maintaining compliance because acute alarms are addressed promptly (Romano and Akhmouch, 2019). Operators respond to threshold exceedances, adjust treatment processes when alerts indicate drift, and assume that if no critical alarms are sounding, performance remains within acceptable bounds. Meanwhile, compliance officers reviewing aggregated data at head office observe that cumulative metrics are trending toward regulatory limits—95th percentile values creeping upward, frequency of exceedances increasing even if individual events remain below alarm thresholds—but lack the operational context to understand why performance is degrading or what interventions might arrest the trend.

By the time a formal compliance breach is recorded—when cumulative metrics cross regulatory thresholds—the window for corrective action has long since closed (Rasmussen, 1997). Site staff, who possess the operational knowledge to diagnose causes and implement adjustments, learn of the breach only after regulatory notification. The opportunity to address systemic drift through process optimisation, equipment maintenance, or operational modification is lost. What might have been managed as gradual performance tuning becomes a compliance failure requiring a formal investigation, remedial action plans, and potential regulatory sanctions.

This is not a failure of monitoring technology; the instruments function as designed, and data streams provide the visibility regulators require. Nor is it a failure of individual competence: site engineers are skilled at responding to acute events, and compliance officers diligently track regulatory obligations. The failure is architectural: responsibility for compliance assurance has been structurally separated from the operational competence required to sustain it. Head office staff have visibility into cumulative trends but lack the system knowledge to interpret drift or recommend interventions. Site staff have system knowledge and operational control but lack visibility into whether their responses are sufficient to maintain compliance over regulatory timeframes.

The most sophisticated monitoring infrastructure cannot ensure compliance if the people capable of diagnosing and correcting performance trends are systematically excluded from

the data that reveals those trends. In contrast, those monitoring cumulative compliance lack the operational literacy to act appropriately before thresholds are breached. Smart systems were intended to enable proactive management; instead, this configuration produces a more fragile form of assurance, where compliance is monitored but not sustained, reported but not enacted through operational practice.

The persistence of this architectural failure warrants examination. Organisations often possess documented protocols that ostensibly address these coordination gaps: procedures specifying who reviews cumulative compliance data, at what frequency, and with what authority to request operational adjustments. Management may assert that these protocols ensure adequate communication between head office compliance functions and site operational teams. Yet in practice, staff shortages, skills gaps, and competing operational priorities mean that documented processes are inconsistently enacted. The complexity is compounded when sites operate hybrid infrastructures: ageing equipment with manual or legacy SCADA monitoring alongside smart sensors with cloud-based dashboards, each system generating data in different formats, at different frequencies, with different access protocols. Site engineers managing this technical heterogeneity—ensuring older assets remain operational while integrating newer digital systems—lack the capacity to systematically track whether head office reviews are occurring, whether compliance trends are being communicated, or whether their operational responses are sufficient to address cumulative drift.

The result is a reliability governance failure that operates in plain sight yet remains organizationally invisible. When compliance breaches occur, investigations typically reveal that protocols existed but were not followed, that communication channels were defined but not used, and that operational adjustments were possible but not requested in time. The response is often procedural: update the protocol, clarify responsibilities, emphasise the importance of communication. What remains unaddressed is the structural condition that produced the failure: visibility architecture that separates compliance monitoring from operational competence, in organisational contexts where resource constraints prevent documented coordination mechanisms from functioning as designed.

Smart water systems do not fail because technology is inadequate; they fail because the sociotechnical integration required to sustain reliability has not been resourced, validated, or governed as seriously as the technical infrastructure itself.

These five patterns—sensory knowledge erosion, commissioning validation without interpretive support, asymmetric visibility, and compliance by proxy—illustrate why professional adaptation is not optional. Engineers must cultivate new competences: the ability to articulate tacit knowledge in ways that bridge sensory and digital epistemologies, the capacity to validate not just technical correctness but sociotechnical functionality, and the organisational literacy to recognise when visibility structures inadvertently compromise the reliability they were designed to enhance. Traditional apprenticeship models and commissioning-as-checklist practices are insufficient for these demands. Adaptation is required, yet frameworks for what adaptation entails—and how it might be resourced, recognised, and sustained—remain underdeveloped.

4. Minimal Theoretical Frame

The patterns described in this paper are derived from long-term industry observation rather than from a single empirical study. They reflect repeated configurations encountered across commissioning, operational assurance, and system optimisation activities in multiple water and wastewater contexts, including both digitally mature and transitional environments. These observations are synthesised analytically to identify recurring competence gaps and organisational dynamics, rather than to provide statistical generalisation. The intent is not to claim exhaustive coverage, but to articulate patterns that practitioners consistently recognise yet lack a shared conceptual language to describe

While the focus of this paper is industry-led, a minimal theoretical frame is necessary to situate Smart Water Reliability within existing scholarship. Reliability engineering has long emphasised lifecycle assurance, recognising that performance must be sustained across design, commissioning, operation, and maintenance (ISO, 2024; Smith and Simpson, 2009). Yet this tradition has often privileged technical robustness and measurable outcomes, leaving the human competences required to sustain reliability underexplored (Leveson, 2017).

While SWR draws on established scholarship in safety science, sociotechnical systems, and professional practice, it identifies and theorises a phenomenon that existing frameworks do not adequately capture: the redistribution of reliability work in digitally mediated critical infrastructure. Classical reliability engineering foregrounds technical robustness and measurable outcomes; asset management emphasises lifecycle planning and maintenance optimisation; high-reliability organisation theory focuses on mindful organising and collective sensemaking. None of these frameworks adequately theorises how professional competence shifts when digital visibility mediates operational practice, creating new patterns of invisible work, attention triage, and distributed accountability.

Workplace learning research highlights the dominance of tacit knowledge in engineering practice (Eraut, 2004; Polanyi, 2009). Informal apprenticeship models have historically transmitted competence, but they struggle to account for the interpretive judgment now required in digitally mediated environments. Professional identity studies further show that legitimacy is negotiated rather than given, underscoring the importance of recognising diverse forms of contribution in reliability work (Trede et al., 2012).

Sociotechnical systems theory provides a final anchor, emphasising that technical artefacts and organisational practices are inseparable (Baxter and Sommerville, 2011; Trist and Bamforth, 1951). Reliability is not produced by assets alone, nor by data streams in isolation, but through the continuous interaction of technology, people, and organisational routines (Hollnagel et al., 2006). These literatures provide scaffolding for the industry observations presented here, but it is not the central focus. Smart Water Reliability is introduced primarily as a lens for understanding how reliability is enacted in practice under conditions of digitalisation, sustainability pressures, and systemic complexity.

The absence of dedicated commissioning scholarship in peer-reviewed literature reflects the discipline's historical positioning as technical execution rather than knowledge work—a gap this paper begins to address.

5. Implications for Industry

The findings of this paper carry significant implications for how reliability is understood, governed, and sustained in smart water systems. While digital technologies are introduced as tools to improve visibility, control, and efficiency, their most significant effects are frequently organisational and behavioural (Orlikowski, 2007). As digital mediation becomes embedded in everyday practice, it reshapes how judgment is exercised, how responsibility is allocated, and how action is legitimised (Suchman, 2006).

5.1 Re-centring Professional Judgement in Data-Mediated Practice

One of the most significant implications of data-rich operational environments is the repositioning of professional judgement. As operational performance becomes increasingly represented through interpreted data, judgment may be reframed as confirmatory rather than constitutive of system understanding (Endsley, 1995; Rosenhead et al., 2019). In such settings, experiential knowledge, contextual reasoning, and discretionary assessment risk are treated as secondary to formally represented indicators.

From a practice perspective, this shift can have subtle but far-reaching consequences. When judgment is expected to align with data representations rather than interrogate them, the capacity to question apparent stability or to recognise emerging anomalies may be reduced. Over time, this can narrow the range of acceptable interpretations and constrain the space within which professional expertise is exercised.

Re-centring judgement does not imply rejecting digital mediation or privileging intuition over evidence. Instead, it involves recognising judgment as an essential interpretive activity that gives meaning to data. Organisational arrangements that explicitly legitimise questioning, contextual interpretation, and discretionary intervention are better positioned to manage uncertainty in complex systems than those that treat data representations as definitive.

5.2 Aligning Visibility with Authority and Accountability

Data-rich environments often expand visibility more rapidly than they clarify authority. While performance information may be widely accessible across organisational layers, responsibility for acting on that information may remain ambiguous. This misalignment can create conditions in which emerging risks are visible to many but owned by none.

In practice, this diffusion of responsibility can delay intervention, particularly when signals are ambiguous or remain within accepted performance envelopes (Vaughan, 2016). Individuals may hesitate to act without explicit authorisation, while those with formal authority may assume that others closer to operations will respond if necessary. Over time, such dynamics can normalise inaction in the presence of weak or equivocal signals.

Addressing this issue requires explicit alignment between visibility and authority. Decision rights, escalation pathways, and intervention thresholds should be articulated not only in procedural terms, but in ways that recognise the interpretive nature of operational risk. Clarifying who is expected to act, and under what conditions, can reduce reliance on implicit assumptions and support more timely responses to emerging concerns.

5.3 Attending to Cumulative and Temporal Risk

Another implication concerns the temporal dynamics of risk accumulation in data-mediated systems. Digital representations often foreground current performance states, encouraging short-term assessments of stability or compliance. However, many operational risks emerge gradually, through the accumulation of small deviations, deferred interventions, or sustained operating compromises.

Where attention is focused primarily on immediate indicators, longer-term patterns may receive insufficient scrutiny. Early signs of degradation may be recognised informally but remain unaddressed until thresholds are breached or performance deteriorates visibly. By the time intervention occurs, options for mitigation may be constrained, and responsibility for earlier inaction difficult to assign (Rasmussen, 1997).

Practitioners and organisations may therefore benefit from developing practices that explicitly attend to temporal risk. This includes recognising that apparent stability does not necessarily indicate resilience, and that cumulative effects may be masked by acceptable short-term performance. Incorporating longitudinal perspectives into routine review and decision-making processes can help counteract the tendency for risk to remain latent until disruptive events occur.

5.4 Developing New Forms of Training and Professional Formation

Traditional training approaches—apprenticeship models, hands-on commissioning, and learning-by-doing—are being displaced by digital-first operational environments. Yet these traditional approaches were precisely how engineers developed the tacit knowledge and interpretive judgement now being eroded.

Training must evolve to prepare engineers for:

Tacit Competence Formalization: Engineers must be trained to articulate and share tacit knowledge, rather than relying solely on informal apprenticeship. This includes developing language and frameworks for sensory expertise (the pump that "sounds wrong"), pattern recognition (the dashboard that "looks odd"), and experiential judgement (when to intervene despite data saying otherwise).

Interpretive Judgement Under Uncertainty: Training should emphasize decision-making under uncertainty, including when to act and when to hold back. This is not binary technical validation but continuous professional judgement in ambiguous conditions—precisely the competence that data-deference undermines.

Multicultural Participation: Engineers must be prepared for diverse communication norms, where silence or restraint can signal respect and careful judgement rather than disengagement. Digital environments can amplify cultural misinterpretation when participation is equated with vocal contribution.

Critical Digital Literacy: Smart water reliability depends on smart monitoring systems; personnel must be trained to interpret data critically rather than treating it as infallible. This

includes understanding algorithmic limitations, sensor failure modes, and the gap between represented performance and operational reality (Billett, 2011).

5.5 Recognizing New Personnel Roles

Smart Water Reliability introduces or elevates roles that are critical for reliability but often invisible in traditional commissioning structures:

Reliability Integrators: Professionals who bridge technical validation with organizational routines, ensuring commissioning is continuous rather than discrete. These individuals translate between digital systems, operational practice, and management expectations.

Tacit Knowledge Stewards: Senior engineers tasked with capturing and transmitting experiential insights before they retire. This role makes explicit the informal mentoring that historically sustained reliability competence.

Participation Facilitators: Personnel who ensure diverse voices are recognized in commissioning, reducing the risk of exclusion based on communication style, seniority, or cultural background.

Digital Reliability Analysts: Specialists who interpret sensor data and integrate it with organisational judgment, bridging the gap between data streams and operational decision-making.

These roles are not entirely new—elements of them exist in current practice—but they are rarely formalised, resourced, or recognised in organisational structures or professional development pathways (Star and Strauss, 1999).

5.6 Organisational and Policy Implications

Curricula must expand to include commissioning competences beyond technical validation, preparing graduates for continuous reliability assurance roles. Workforce planning should explicitly recognise and resource these personnel categories rather than assuming competence emerges informally. Standards bodies may need to update commissioning guidelines to reflect sociotechnical training requirements, moving beyond technical checklists to encompass interpretive and coordinative competences.

6. Conclusion

The reliability of water systems can no longer be assured through static commissioning milestones or periodic validation alone (ISO, 2024; Rasmussen, 1997). Digitalisation, sustainability pressures, and systemic complexity have transformed reliability into a continuous practice, sustained through the interaction of technology, professional judgement, and organisational adaptation (Hollnagel et al., 2006; Perrow, 2011). Smart Water Reliability provides a framing concept for understanding this transformation.

By situating reliability as an ongoing negotiation between digital visibility and human interpretation, the paper highlights the competences now required of engineers: interpretive

judgement, coordination, and adaptive decision-making (Endsley, 1995; Eraut, 2004). These forms of work are often less visible than technical validation, yet they are increasingly central to sustaining performance under conditions of uncertainty (Star and Strauss, 1999; Weick and Sutcliffe, 2001).

For industry, the implications are clear. Training, standards, and organisational planning must evolve to recognise reliability as sociotechnical sustainability rather than a discrete technical achievement. Regulators and professional bodies must embed continuous assurance into their expectations, while organisations must resource the tacit and interpretive dimensions of reliability work (ISO, 2024; WHO, 2017).

Smart Water Reliability is not proposed as a new standard or prescriptive model, but as a lens through which industry can recognise and respond to the changing demands of reliability practice (Power, 2007). Positioned globally, it provides the conceptual anchor for subsequent research and applied studies, ensuring that debates on identity, culture, safety, and competence are grounded in the broader transformation of reliability itself (Pahl-Wostl, 2006; Romano and Akhmouch, 2019).

6.1 Smart Water Reliability as a Framing Concept

This paper has introduced Smart Water Reliability (SWR) as a framing device for understanding how reliability is produced and sustained in digitally mediated water systems. Unlike traditional approaches that treat reliability as a static attribute assured at commissioning, SWR highlights the ongoing redistribution of reliability work across digital visibility, professional judgement, and organisational adaptation.

Five competence patterns illustrate this transformation: the erosion of sensory knowledge, signal saturation and attention triage, the commissioning blind spot, asymmetric visibility, and compliance by proxy. Together, these patterns show that sustaining reliable performance depends not only on technical assets and algorithms, but on the interpretive and coordinative capacities of engineers and operators.

By foregrounding these competences, SWR contributes to both practice and scholarship. For practitioners, it clarifies the forms of expertise now required to sustain reliable performance under conditions of uncertainty and continuous monitoring. For researchers, it offers a conceptual lens that extends beyond technical robustness to encompass the sociotechnical work of reliability. In doing so, SWR provides a foundation for future inquiry and industry adaptation, positioning reliability not as a one-time certification but as a dynamic, negotiated process central to the future of water engineering.

Declaration of Generative AI Use

The authors used AI-assisted tools (Grammarly) to support grammar and editorial refinement during manuscript preparation. All substantive arguments, theoretical frameworks, and industry observations presented in this paper are the authors' original intellectual work, grounded in over 60 combined years of commissioning practice. The authors take full responsibility for the accuracy and integrity of the content.

References

Bach, P.M., Rauch, W., Mikkelsen, P.S., McCarthy, D.T., Deletic, A., 2014. A critical review of integrated urban water modelling – Urban drainage and beyond. Environ. Model. Softw. 54, 88–107. https://doi.org/10.1016/j.envsoft.2013.12.018

Baxter, G., Sommerville, I., 2011. Socio-technical systems: From design methods to systems engineering. Interact. Comput. 23, 4–17. https://doi.org/10.1016/j.intcom.2010.07.003

Billett, S., 2011. Vocational Education: Purposes, Traditions and Prospects. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-007-1954-5

Brown, R.R., Keath, N., Wong, T.H.F., 2009. Urban water management in cities: historical, current and future regimes. Water Sci. Technol. 59, 847–855. https://doi.org/10.2166/wst.2009.029

Dekker, S., 2017. The Field Guide to Understanding 'Human Error,' 3rd ed. CRC Press. https://doi.org/10.1201/9781317031833

Eggimann, S., Mutzner, L., Wani, O., Schneider, M.Y., Spuhler, D., Moy De Vitry, M., Beutler, P., Maurer, M., 2017. The Potential of Knowing More: A Review of Data-Driven Urban Water Management. Environ. Sci. Technol. 51, 2538–2553. https://doi.org/10.1021/acs.est.6b04267

Endsley, M.R., 1995. Toward a Theory of Situation Awareness in Dynamic Systems. Hum. Factors J. Hum. Factors Ergon. Soc. 37, 32–64. https://doi.org/10.1518/001872095779049543

Eraut, M., 2004. Informal learning in the workplace. Stud. Contin. Educ. 26, 247–273. https://doi.org/10.1080/158037042000225245

Flyvbjerg, B., 2014. What you Should Know about Megaprojects and Why: An Overview. Proj. Manag. J. 45, 6–19. https://doi.org/10.1002/pmj.21409

Gao, Y., Janssen, M., Zhang, C., 2023. Understanding the evolution of open government data research: towards open data sustainability and smartness. Int. Rev. Adm. Sci. 89, 59–75. https://doi.org/10.1177/00208523211009955

Hodkiewicz, M.R., 2015. The Development of ISO 55000 Series Standards, in: Tse, P.W., Mathew, J., Wong, K., Lam, R., Ko, C.N. (Eds.), Engineering Asset Management - Systems, Professional Practices and Certification, Lecture Notes in Mechanical Engineering. Springer International Publishing, Cham, pp. 427–438. https://doi.org/10.1007/978-3-319-09507-3_37

Hollnagel, E., Woods, D., Leveson, N., 2006. Resilience Engineering : Concepts and Precepts. Resil. Eng. Concepts Precepts.

Hopkins, A., 2012. Disastrous Decisions: The Human and Organisational Causes of the Gulf of Mexico Blowout.

ISO, 2024. ISO 55000: Asset Management – Overview, Principles and Terminology (No. 2).

Leveson, N.G., 2017. Engineering a safer world: systems thinking applied to safety, New paperback edition. ed, Engineering systems. The MIT Press, Cambridge, London, England.

Love, P.E.D., Edwards, D.J., Smith, J., 2016. Rework Causation: Emergent Theoretical Insights and Implications for Research. J. Constr. Eng. Manag. 142, 04016010. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001114

Makropoulos, C.K., Butler, D., 2010. Distributed Water Infrastructure for Sustainable Communities. Water Resour. Manag. 24, 2795–2816. https://doi.org/10.1007/s11269-010-9580-5

Mounce, S.R., Khan, A., Wood, A.S., Day, A.J., Widdop, P.D., Machell, J., 2003. Sensor-fusion of hydraulic data for burst detection and location in a treated water distribution system. Inf. Fusion 4, 217–229. https://doi.org/10.1016/S1566-2535(03)00034-4
Orlikowski, W.J., 2007. Sociomaterial Practices: Exploring Technology at Work. Organ. Stud. 28, 1435–1448. https://doi.org/10.1177/0170840607081138
Pahl-Wostl, C., 2006. Transitions towards adaptive management of water facing climate and global change. Water Resour. Manag. 21, 49–62. https://doi.org/10.1007/s11269-006-9040-4
Perrow, C., 2011. Normal Accidents: Living with High Risk Technologies - Updated Edition. Princeton University Press, Princeton, NJ. https://doi.org/10.1515/9781400828494
Poch, M., Comas, J., Rodríguez-Roda, I., Sànchez-Marrè, M., Cortés, U., 2004. Designing and building real environmental decision support systems. Environ. Model. Softw. 19, 857–873. https://doi.org/10.1016/j.envsoft.2003.03.007
Polanyi, M., 2009. The tacit dimension, Reproduction en fac-similé. ed. University of Chicago press, Chicago.
Power, M., 2007. Organized Uncertainty: Designing A World of Risk Management, Public Administration. https://doi.org/10.1111/j.1467-9299.2008.00756_2.x
Rasmussen, J., 1997. Risk management in a dynamic society: a modelling problem. Saf. Sci. 27, 183–213. https://doi.org/10.1016/S0925-7535(97)00052-0
Reason, J., 2016. Managing the Risks of Organizational Accidents, 1st ed. Routledge. https://doi.org/10.4324/9781315543543
Romano, O., Akhmouch, A., 2019. Water Governance in Cities: Current Trends and Future Challenges. Water 11, 500. https://doi.org/10.3390/w11030500
Rosenhead, J., Franco, L.A., Grint, K., Friedland, B., 2019. Complexity theory and leadership practice: A review, a critique, and some recommendations. Leadersh. Q. 30, 101304. https://doi.org/10.1016/j.leaqua.2019.07.002
Smith, D.J., Simpson, K.G.L., 2009. Functional safety: a straightforward guide to applying IEC 61508 and related standards. Elsevier, Boston.
Star, S.L., Strauss, A., 1999. Layers of Silence, Arenas of Voice: The Ecology of Visible and Invisible Work. Comput. Support. Coop. Work CSCW 8, 9–30. https://doi.org/10.1023/A:1008651105359
Suchman, L., 2006. Human-Machine Reconfigurations: Plans and Situated Actions, 2nd ed. Cambridge University Press. https://doi.org/10.1017/CBO9780511808418
Trede, F., Macklin, R., Bridges, D., 2012. Professional identity development: a review of the higher education literature. Stud. High. Educ. 37, 365–384. https://doi.org/10.1080/03075079.2010.521237
Trist, E.L., Bamforth, K.W., 1951. Some Social and Psychological Consequences of the Longwall Method of Coal-Getting: An Examination of the Psychological Situation and Defences of a Work Group in Relation to the Social Structure and Technological Content of the Work System. Hum. Relat. 4, 3–38. https://doi.org/10.1177/001872675100400101
Vaughan, D., 2016. The Challenger launch decision: risky technology, culture, and deviance at NASA ; with a new preface, Enlarged edition. ed. The University of Chicago Press, Chicago London.
Weick, K.E., Sutcliffe, K.M., 2001. Managing the unexpected: assuring high performance in an age of complexity, University of Michigan Business School management series. Jossey-Bass, San Francisco.
WHO, 2017. Water safety plan manual: step-by-step risk management.