

## Article

# Integrated Management of the Urban Water Cycle: A Synthesis of Impacts and Solutions from Source to Tap

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## Abstract

Urbanization fundamentally fractures the natural water cycle, leading to a cascade of interconnected problems including increased flood risk, degraded water quality, stressed groundwater resources, and inefficient distribution networks. Traditional, fragmented management approaches that address these issues in isolation have proven inadequate. This research argues for a paradigm shift towards an Integrated Urban Water Management (IUWM) framework anchored in the concept of the “river-aquifer-pipe network continuum”, treating these components as a single, dynamic hydrological and infrastructural entity. Drawing upon a series of detailed case studies from Eastern Romania, this paper synthesizes the systemic impacts of development across the entire urban water system. Evidence from the Prut, Olt, and Bahlui river basins demonstrate how channelization exacerbates flood peaks and leads to severe biochemical degradation. Hydrogeological modeling of the Gherăești-Bacău wellfield reveals the vulnerabilities of over-extraction, while analysis of the Iasi water network highlights the challenge of water losses in the aging infrastructure. In response, a modern, multi-tool approach is consolidated into a practical, three-stage framework for action: Diagnose, Prescribe, and Optimize. This framework advocates for (1) a comprehensive diagnosis using a suite of predictive numerical models (a “digital twin”); (2) the prescription of foundational, nature-based solutions, such as floodplain restoration, to heal core ecological functions; and (3) the continuous optimization of engineered infrastructure using smart, real-time control technologies. The synthesis concludes that an integrated, data-driven, and collaborative approach is the only sustainable path forward. Future research should focus on formally coupling these diagnostic models to create true Digital Twins of urban water systems—an essential step towards building resilient, water-secure cities for the 21st century.

**Keywords:** Integrated Urban Water Management; urban water cycle; predictive modeling; nature-based solutions; urban water resilience



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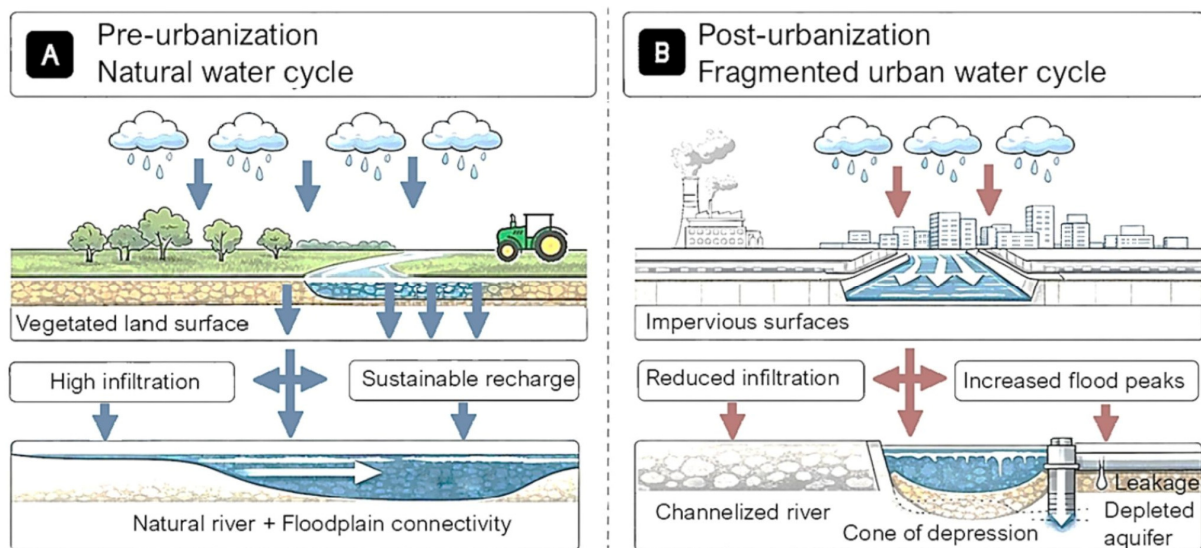
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## 1. Introduction

The relationship between cities and water is a fundamental paradox of the modern era [1]. While urban centers are wholly dependent on reliable water resources for their survival and growth, the very process of urbanization systematically disrupts the natural water cycle that sustains them [2]. The transformation of natural landscapes into built environments—characterized by impervious surfaces, engineered drainage, and channelized rivers—creates a deeply fragmented hydrological system, as seen in Figure 1. This “fractured cycle” manifests in a cascade of interconnected problems: stormwater, once a source of groundwater recharge, becomes a flood risk to be evacuated rapidly; rivers, once dynamic ecosystems, are reduced to concrete conduits for wastewater and runoff; and aquifers, once sustainably replenished, are subjected to relentless extraction pressure [3]. This compartmentalized approach, where stormwater management, river engineering, and water supply are treated as separate, often conflicting, disciplines, has led to a legacy of environmental degradation and infrastructural vulnerability [4]. The consequences are now globally recognized, ranging from an increased frequency of urban floods and the deterioration of aquatic ecosystems to the depletion of vital groundwater reserves, threatening the long-term resilience of cities worldwide [5].



**Figure 1.** The transition from an integrated natural water cycle (A) to a fractured urban water cycle (B). The pre-development state maintains hydrological balance through natural infiltration and floodplain connectivity, whereas the post-urbanization state is dominated by rapid runoff, disconnected channelized rivers, severe groundwater depletion, and infrastructural inefficiencies.

Addressing the failures of this fragmented approach requires a fundamental paradigm shift. The traditional, siloed model of water management, which often prioritizes “hard engineering” solutions to control nature, is proving increasingly unsustainable in the face of climate change and growing urban populations [6]. In its place, a more holistic and resilient philosophy is emerging: Integrated Urban Water Management (IUWM). This paradigm moves beyond the simple management of water as a commodity and re-establishes it as the central, unifying element of the urban ecosystem [7].

Central to this approach is the recognition of the “river-aquifer-pipe network continuum”. This framing suggests that the hydraulic and biochemical state of urban rivers directly influences aquifer health, which in turn defines the operational boundary conditions and stresses of the water distribution infrastructure [8]. It advocates for strategies that mimic natural processes, such as the “Retain, Store, Drain” concept (also known as the “Hold, Store, Drain” concept), which treats rainwater as a valuable resource to be held

in the landscape rather than a nuisance to be discarded. This philosophy champions the transition from rigid, gray infrastructure to flexible, “soft engineering” and nature-based solutions that restore ecological functions while still meeting human needs.

The goal is no longer to conquer water, but to collaborate with its natural dynamics, creating urban environments that are not only protected from water-related risks but are also enhanced by them.

The transition from a fragmented to an integrated water management paradigm requires a comprehensive understanding of both the problems and the available solutions across the entire urban water cycle [9]. While the principles of IUWM are well-established, their application in specific regional contexts, particularly those with a legacy of 20th-century hydraulic engineering, remains a critical area of research [10].

This research aims to contribute to this discourse by synthesizing research focused on a representative region in Eastern Europe, namely North-East Romania. The objectives of this research are threefold:

- (1) To systematically document the impacts of urbanization on surface water, groundwater, and distribution infrastructure, using a series of detailed case studies from Romania as evidence;
- (2) To consolidate a modern “toolbox” of engineering and modeling solutions capable of addressing these multifaceted challenges;
- (3) To propose a cohesive conceptual framework that integrates these tools into a practical strategy for action.

Methodologically, this paper employs an integrative approach, synthesizing disparate technical datasets—including numerical modeling outputs, water quality measurements, and real-time network telemetry—into a unified analytical narrative. By sequentially examining the water system from its natural source to the consumer’s tap, this research moves beyond isolated technical reporting. It actively demonstrates the critical, mutually reinforcing interdependencies between these components and argues for a holistic, data-driven management approach as the only viable path toward creating resilient and water-secure cities.

## 2. The Systemic Impacts of Urbanization on Water Bodies: A Cascade of Degradation

The idealized, integrated urban water cycle remains a distant goal for most cities, which are still grappling with the consequences of decades of fragmented engineering [11]. The impacts of this approach are not isolated; they form a cascade of degradation that propagates from natural water bodies through to the engineered systems designed to control them, as can be seen in Figure 2. This section synthesizes evidence from a series of case studies to illustrate critical areas of impact: the alteration of surface water regimes [12], the increasing stress on groundwater resources [13], and the systemic failure of aging water distribution infrastructure [14].

Although this “cascade” of events is presented sequentially in the following subsections for analytical and pedagogical clarity, it is crucial to recognize that these processes rarely operate as a strict, linear deterministic chain. In the reality of complex urban environments, these mechanisms occur concurrently and form mutually reinforcing feedback loops. For example, while aquifer over-extraction increases vulnerability (Section 2.4), the concurrent biochemical degradation of surface waters (Section 2.2) provides the very contaminants that threaten that aquifer. Simultaneously, failing distribution infrastructure (Section 2.5) not only loses treated water but can leak it back into the subsurface, further altering local groundwater chemistry and soil stability. Therefore, the “cascade” should

be understood not just as a timeline, but as a highly synergistic web of degradation where each failing component accelerates the decline of the others.



**Figure 2.** The Cascade of Degradation.

### 2.1. Hydraulic and Morphological Alteration of River Systems

The most immediate and visually dramatic impact of urban and agricultural development on riverine ecosystems is the physical constraint and radical reshaping of their corridors [15]. Driven by the objectives of maximizing land for development and providing localized flood protection, the conventional 20th-century engineering paradigm favored aggressive, structural interventions [16]. This approach, often termed “hard engineering” as detailed in the review of environmental planning solutions [17], relied on tools like channelization, straightening, and the construction of extensive, un-submersible embankments. This philosophy reached its zenith in projects like the complete concrete encasement of the Los Angeles River, which transformed a dynamic river into a sterile flood-control channel, effectively erasing its ecological identity. The primary function of such works is to enforce a static, predictable geometry upon a naturally dynamic system, fundamentally altering its character and function [18].

The most critical consequence of this paradigm is the abrupt severing of the river’s lateral connectivity with its floodplain. This “disconnected floodplain” syndrome is one of the most widely documented impacts of river regulation globally. In its natural state, a river like the Prut existed within a complex mosaic of meanders, oxbow lakes (*privale*), and backwater channels (*japşe*), as documented in the historical analysis of the Trifeşti-Sculeni enclosure [19]. This intricate landscape served not only as a hydraulic buffer but also as a crucial zone for nutrient cycling and as essential spawning and nursery grounds for fish populations. The large-scale straightening and diking of major European rivers like the Rhine, beginning with the Tulla correction in the 19th century, led to the loss of over 85% of its historical floodplain, with devastating consequences for biodiversity that international commissions are now spending billions to reverse [20].

This confinement fundamentally alters the hydraulics of flood propagation, a process governed by the principles of open-channel flow described by the Saint-Venant equations [21]. When the expansive storage volume of the floodplain is removed, the entire flood discharge is forced through a geometrically constricted channel, leading to higher flow

velocities and a reduction in wave travel time. Tangible evidence of this phenomenon is provided by the long-term hydrological data from the Prut River, where post-embankment hydrographs consistently demonstrate sharper and significantly higher flood peaks compared to the natural, pre-regulation regime [17].

In order to quantify the aforementioned impacts, the analysis employed a multi-year hydrological data set from the Ungheni gauging station, which spans a period of 50 years from 1961 to 2010. This period is of critical importance as it encompasses two distinct regimes: the natural flow regime, preceding the substantial hydraulic works of the 1970s; and the regulated regime, following the inauguration of the Stânca-Costești reservoir in 1978 and the embankment of the Trifești-Sculeni sector. Consequently, it provides a statistically significant foundation for the evaluation of anthropogenic alterations [19].

This effect is not merely a local phenomenon; it creates a dangerous socio-economic feedback loop known as the “levee effect” [22]. As seen tragically along the Mississippi River, the construction of levees encourages a false sense of security, leading to intensified development in the “protected” floodplain. When a flood inevitably exceeds the design capacity, the resulting levee failure is catastrophic, causing far greater damage than would have occurred under natural flooding conditions [23].

A river system subjected to such concentrated hydraulic energy will inevitably attempt to readjust its morphology. Unable to dissipate energy by spreading out laterally, the river’s force is directed vertically, leading to channel incision (thalweg lowering), and against the constrained banks [24]. This process is starkly documented on regulated sections of the Olt River, where comparative cross-sections reveal significant bed degradation over time [17]. This incision can lower the adjacent water table, impacting riparian vegetation, and lead to “sediment starvation” in downstream reaches and deltas, which rely on a steady supply of sediment to maintain their form. The disastrous consequences of this process were famously demonstrated in the Kissimmee River in Florida, which, after being channelized into a straight ditch in the 1960s, saw its vast wetland ecosystem collapse [25]. The subsequent, decades-long, multi-billion-dollar project to re-meander the river stands as a powerful testament to both the scale of the damage caused by channelization and the immense difficulty and cost of reversing it. Thus, the physical alteration of the river corridor sets off a cascading series of hydraulic and morphological instabilities that not only degrade the ecosystem but, paradoxically, often create new and more severe long-term risks for human society [26].

## 2.2. Biochemical Degradation of Surface Waters

The alteration of a river’s physical and hydraulic regime is invariably followed by a severe decline in its water quality [27]. This degradation is not merely an additive process of pollution but a systemic failure of the river’s ecological functions. Natural, unconfined river systems possess a remarkable capacity for self-purification, a concept central to river ecology. This capacity is primarily delivered through the ecosystem services of its connected floodplains, wetlands, and complex in-stream habitats [28]. These areas act as vast biological and chemical reactors, where slow-moving water allows for the settling of suspended solids, while microbial communities in sediments and on plant surfaces actively process and remove pollutants, most notably through the process of denitrification, which converts harmful nitrates into harmless nitrogen gas [29].

When these features are eliminated through channelization and embankment, the river’s self-purification capacity is drastically reduced. The system is transformed from a complex, processing ecosystem into a simple, efficient conduit for urban, industrial, and agricultural contaminants.

The Bahlui River, which flows through the major urban center of Iași, serves as a stark example of this biochemical degradation [30]. Detailed water quality modeling of the river provides a textbook illustration of the consequences.

The Bahlui River, which flows through the major urban center of Iași, serves as a stark example of this biochemical degradation [30]. The calibration of the hydrodynamic and water quality models for this urban river sector was conducted using high-resolution flow and physicochemical datasets (dissolved oxygen, biochemical oxygen demand, temperature) collected during the 2008–2012 monitoring campaigns. It is important to acknowledge the temporal limitation of this dataset. In the intervening years, the municipal wastewater treatment infrastructure serving the Iași metropolitan area has undergone significant upgrades, which have likely improved the baseline, dry-weather water quality.

However, utilizing this specific temporal window is analytically vital for this synthesis. It serves as a documented “stress-test” baseline, representing typical urban hydrological stress conditions and capturing seasonal variations in pollutant dilution capacity. Because the physical inability of the engineered, channelized river to self-purify remains unchanged, high-intensity rainfall events, untreated urban runoff, and combined sewer overflows (CSOs) can still trigger acute pollution episodes.

The model based on these stress conditions simulates a classic dissolved oxygen (DO) sag curve, a phenomenon first described by Streeter and Phelps in their foundational studies of the Ohio River [31]. The results show a precipitous drop in DO levels to near-anoxic conditions, occurring in direct correlation with a sharp increase in biochemical oxygen demand (BOD) to values exceeding those acceptable for healthy aquatic life. This is the unmistakable signature of an overwhelming organic pollution load that has completely exhausted the river’s diminished assimilative capacity. This vulnerability underscores a core premise of our proposed framework: historical, static infrastructural upgrades cannot guarantee water security without the continuous, real-time monitoring and adaptive responses advocated by the DPO model.

Furthermore, the water quality of the Prut River, the source for the regional re-naturation project, while better (Class II quality), still shows significant levels of total suspended solids (average 48.85 mg/L, max 113.00 mg/L) and BOD<sub>5</sub> (average 4.12 mg/L, max 7.40 mg/L), indicating the pervasive pressure of diffuse pollution even in larger river systems [19]. This pattern of severe biochemical degradation is common in urbanized rivers worldwide. The historic pollution of the River Thames in London, which was declared ‘biologically dead’ in 1957 due to untreated sewage discharges, is a famous example [32]. Similarly, the Cuyahoga River in Ohio became infamous for catching fire on multiple occasions due to industrial pollution [33].

While point-source pollution has been significantly reduced in many Western countries through the construction of wastewater treatment plants, the problem of diffuse pollution from agricultural and urban runoff remains a pervasive challenge.

Channelized rivers are particularly poor at handling this type of pollution. Without the filtering capacity of riparian buffers and floodplains, pesticides, fertilizers, and heavy metals are washed directly into the river channel during storm events. This leads to chronic, low-level contamination and episodic, high-concentration pollution events that can cause fish kills and harmful algal blooms.

The “green tides” of algae that plague the coast of Brittany, France, for example, are a direct result of excess nitrates transported from agricultural catchments through channelized river systems [34]. This biochemical degradation ultimately leads to a state of severe ecological distress, rendering the water unfit for most beneficial uses, compromising drinking water sources, and transforming a vital natural artery into an environmental liability.

### 2.3. Quantitative Stress on Aquifer Systems

The pressure of urbanization extends deep beneath the surface, placing unprecedented quantitative stress on groundwater resources. As the most reliable and often highest-quality source of water, alluvial aquifers beneath and adjacent to cities are frequently subjected to intensive extraction to meet rising municipal and industrial demand [35]. This leads to the development of large, strategically placed wellfields that fundamentally alter the natural hydrogeological regime. The Gherăești-Bacău capture front, a critical water source for the city of Bacău, exemplifies this process. Comprising 44 operational boreholes extracting a combined total flow of 190 L/s, this wellfield imposes significant stress on the local aquifer system [36]. Numerical modeling of this system clearly visualizes the result: the creation of an extensive cone of depression, a localized lowering of the piezometric surface that reverses natural hydraulic gradients and changes the direction and velocity of subsurface flow.

In the Bacău wellfield, a total of 57 wells were constructed following the initiation of the water supply system development program, with 8 wells drilled in 1966 and the remaining 49 completed by 1982. The hydrogeological model is based on the lithostratigraphic information derived from these 57 wells; however, it should be noted that only 44 wells were operational during the 2020–2022 period. Consequently, the calibration and validation of the model is contingent on the monitoring and operational data from these active wells. The calibration process resulted in a total hydraulic head error of 0.051 m relative to observed field measurements, indicating a high level of accuracy and are liable representation of the aquifer's response to long-term abstraction [36].

This intensive pumping can easily lead to a state of groundwater overdraft, where extraction rates exceed the natural rate of replenishment from precipitation and river infiltration.

The long-term consequence of overdraft is a decline in water table levels. This is a critical global issue, with some of the world's most important aquifers showing alarming rates of depletion [37]. The Ogallala Aquifer in the central United States, for instance, which supports a significant portion of American agriculture, has seen water levels drop by over 30 m in some areas due to decades of unsustainable pumping for irrigation [38]. Similarly, megacities like Mexico City have experienced dramatic consequences of overdraft, including widespread land subsidence. As water is removed from the pore spaces of sediments, the aquifer compacts, causing the ground surface to sink—in Mexico City's case, by more than 9 m over the last century, severely damaging buildings, infrastructure, and increasing flood risk [39].

In coastal regions, this Hydroinformatics tool's overdraft leads to an even more insidious problem: saltwater intrusion. As freshwater levels in the aquifer decline, the hydraulic pressure that holds back the seawater is reduced, allowing saline water to migrate inland and irreversibly contaminate the aquifer [40]. This phenomenon is turning freshwater resources brackish in coastal cities worldwide, from Florida to the Nile Delta, and is a critical threat to the future of megacities like Jakarta, which faces a dual crisis of sinking land and salinizing wells [41].

Furthermore, over-extraction fundamentally alters the interaction between groundwater and surface water. In a natural state, many rivers are "gaining streams," receiving a steady inflow of cool, clean groundwater that sustains their baseflow during dry periods. This baseflow is ecologically vital, maintaining water levels, moderating temperatures, and diluting pollutants [42]. The powerful cone of depression created by urban wellfields can reverse this dynamic, transforming the river into a "losing stream" that leaks water into the depleted aquifer.

The calibrated model of the Gherăești-Bacău system quantifies this interaction, showing a significant flux from the Bistrița River into the aquifer, which is then captured by the

wells [43]. While this induced infiltration can augment the wellfield's yield, it comes at a direct cost to the river's ecological health. This phenomenon has been observed in river basins worldwide, such as the Platte River in Nebraska, where decades of groundwater pumping for agriculture have significantly reduced summer flows, threatening critical habitats for endangered bird species [44]. This quantitative stress thus not only endangers the long-term sustainability of the water supply itself but also directly compromises the health of the surface water ecosystems to which it is linked.

#### 2.4. Increased Vulnerability of Groundwater Quality

The quantitative stress placed on aquifers increases the vulnerability of their water quality. In a natural, undisturbed state, groundwater is often protected by a combination of overlying, low-permeability geological layers (aquitards) and the natural hydraulic gradient, which typically directs shallow groundwater towards surface water bodies [45]. The large cones of depression created by urban wellfields, however, can overwhelm these natural defenses.

As documented in the Gherăești-Bacău study, these pumping centers create a powerful hydraulic sink that actively draws in water from the surrounding area, including from adjacent rivers [36,43]. This process, known as induced infiltration, establishes a direct pathway for any contaminants present in the surface water to be pulled into the aquifer and, eventually, into the drinking water supply. The close proximity of the Gherăești-Bacău wellfield to the Bistrița River, with boreholes located at an average distance of only 75 m from the riverbed, exemplifies this high-risk scenario. While the predictive modeling for the proposed recreational lake in this specific case showed a manageable impact, it serves to underscore a universal principle: over-extraction compromises the natural protective capacity of an aquifer. It effectively transforms the river-aquifer interface from a complex buffer zone—where contaminants might be filtered, sorbed, or biodegraded over long residence times—into a potential contamination highway. The time it takes for a contaminant to travel from the river to a pumping well can be reduced from decades to mere days or weeks, leaving water utility operators with little to no time to react to a surface water pollution event.

The consequences of this induced vulnerability have been demonstrated in numerous cases worldwide. One of the most famous examples occurred in Walkerton, Canada, in 2000, where heavy rainfall washed manure containing *E. coli* O157:H7 bacteria from a nearby farm into a shallow municipal well. The well's capture zone, amplified by pumping, drew the contaminated surface water directly into the town's unchlorinated water supply, leading to a devastating outbreak that resulted in seven deaths and thousands of illnesses [46].

Similarly, in the 1970s and 80s, industrial solvents, mainly trichloroethene (TCE) and perchloroethene (PCE), from industrial sites in Woburn, Massachusetts, contaminated two municipal wells, leading to a documented cluster of childhood leukemia cases. The wells, located near the Aberjona River, had induced infiltration from the contaminated river and surrounding groundwater, creating a complex plume that delivered the carcinogens to the public [47].

These cases are powerful reminders that the quantitative management of groundwater cannot be decoupled from the management of surface land use and water quality. Every decision to increase pumping rates is also a decision that can potentially shrink the safety margin protecting the quality of the public water supply.

#### 2.5. Degradation of Water Infrastructure: The Challenge of Non-Revenue Water (NRW)

The final stage in this cascade of degradation occurs within the "man-made" portion of the water cycle: the vast, buried web of pipes, pumps, and valves that form the urban water

distribution network. This infrastructure, often out of sight and out of mind, is itself a victim of the urban environment it serves. Supplying water to a city with challenging topography, like Iași, which features an elevation difference of 360 m from the source to the highest consumer, necessitates a high-energy, multi-stage pumping system to maintain adequate service pressures across all zones [48]. However, this high operational pressure, especially when combined with the large diurnal fluctuations between peak morning demand and minimal night flow, places immense and cyclical physical stress on the network.

The inevitable result is a chronic and costly problem known as Non-Revenue Water (NRW), a term that encompasses not only physical losses from leaks and pipe breaks but also apparent losses from metering inaccuracies and unauthorized consumption [49]. The physical losses, often the largest component, are a direct symptom of infrastructure degradation. The Iași network, with a total length of 1426 km and a significant proportion of older materials like asbestos-cement and cast iron, is representative of many aging systems worldwide [50]. High and fluctuating pressures exploit the weakest points in this system—corroded pipe walls, failing joints, and brittle connections—leading to a constant background leakage and frequent, catastrophic main breaks.

Specifically, for the Iași water distribution network, official estimates declared by the regional utility management during public briefings indicate that Non-Revenue Water (NRW) has remained within the range of 30–38% in recent years, accounting for 36.70% in 2021, 35.53% in 2022, 33.35% in 2023, and 37.80% in 2024 of the total raw water input volume [51]. Despite the elevated nature of these values, they are consistent with the structural characteristics of water utilities operating in post-socialist countries in Eastern Europe, particularly in mostly Romanian cities [52].

From a broader European perspective, the lowest average NRW levels are reported in highly optimized systems such as the Netherlands (approximately 5%), Germany (approximately 6%), and Denmark (approximately 8%). In contrast, intermediate to high NRW levels are observed in France (approximately 20%), Belgium (approximately 21%), Poland (approximately 25%), and Slovakia (approximately 32%). A significantly higher incidence of losses has been documented in Italy (approximately 41%), Romania (approximately 44%), and Bulgaria (approximately 60%) [53].

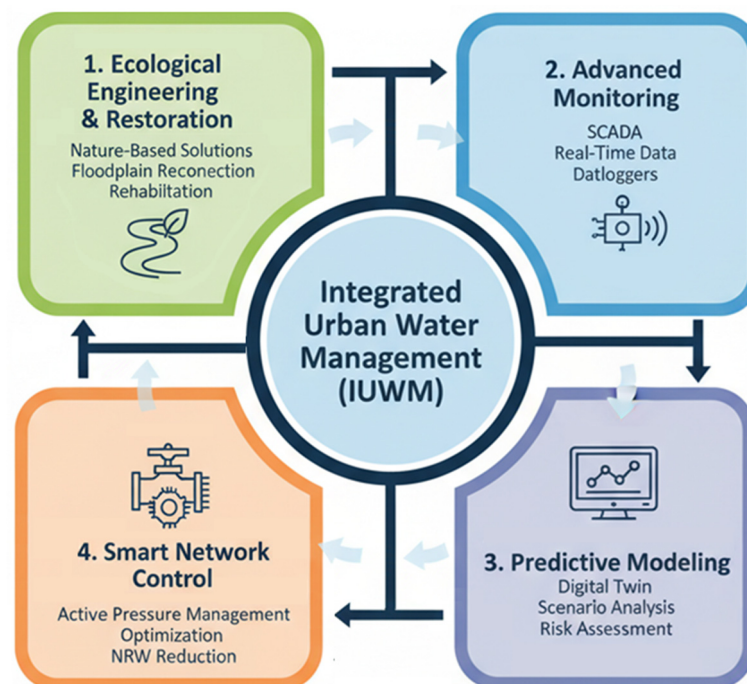
The available comparative data suggest that the situation in Iași is indicative of a broader regional pattern, rather than an isolated anomaly. This pattern is characterized by the effects of aging infrastructure, historical under investment, and systemic inefficiencies in water distribution networks.

The relationship is direct: higher pressures not only increase the likelihood of new breaks but also force more water out of existing, often undetected, leaks. This challenge is a global one. It is estimated that cities worldwide lose tens of billions of cubic meters of treated water each year through leakage. In older European cities like London, where some Victorian-era pipes are still in service, leakage reduction is a constant, multi-billion-pound battle [54]. In developing megacities like Mexico City or São Paulo, NRW levels can exceed 40%, meaning nearly half the water that enters the system never reaches a paying customer [55]. Lost water represents far more than a simple volumetric loss; it is the waste of a highly treated, energy-intensive manufactured product. Each cubic meter of lost water carries with it the embedded costs of abstraction, treatment, and pumping [56]. Furthermore, significant leaks can lead to a loss of pressure in the network, causing service interruptions, and can create a dangerous pathway for contaminant intrusion, where surrounding groundwater can enter the drinking water pipe during low-pressure events. This systemic leakage completes a cycle of profound inefficiency that begins with the mismanagement of the natural river and ends with the costly and wasteful degradation of the very infrastructure built to control and deliver its water.

### 3. A Toolbox for Modern Water Management: From Problem to Solution

In response to the cascade of degradation detailed in the previous section, a new generation of water management tools and approaches has emerged. Moving beyond the limitations of traditional, rigid engineering, this modern toolbox emphasizes integration (as seen in Figure 3), data-driven decision-making, and a collaborative approach with natural systems. It provides the necessary instruments to diagnose complex problems, prescribe effective solutions, and optimize the performance of both natural and engineered water systems. This section outlines four essential components of this toolbox:

- (1) The principles of ecological engineering;
- (2) The technologies for advanced monitoring;
- (3) The power of predictive modeling;
- (4) The precision of smart network control.



**Figure 3.** The four core components of the modern toolbox for Integrated Urban Water Management, highlighting synergy between nature-based, data-driven, and technology-enabled solutions.

#### 3.1. Ecological Engineering and Restoration: Working with Nature, Not Against It

The foundational element of the new water management paradigm is a profound shift in guiding principles: from conquering Nature to collaborating with it. This approach, broadly termed ecological engineering or “soft engineering,” provides a powerful and increasingly necessary alternative to the rigid, gray infrastructure that has historically dominated river management [57]. Instead of eliminating natural processes like flooding and meandering, this philosophy aims to restore and leverage them to achieve a broader set of engineering and societal goals. As demonstrated by the proposed renaturation of the Trifești-Sculeni floodplain on the Prut River, this involves practical, targeted interventions designed to reactivate natural functions within a managed landscape. The proposed solution, which includes a controlled intake to provide a calculated flushing flow of 890 L/s, aims to reconnect the river to its historical backwaters (privale) and wetlands, turning a static, drained agricultural polder back into a dynamic, functional ecosystem [8].

The evaluation of this intervention through the lens of “social-ecological synergy benefits”—an assessment framework that has been increasingly advocated in high-impact

literature [58,59]—has revealed significant quantitative gains. From a hydraulic perspective, the reconnection of the 8130 ha enclosure has the potential to create a flood retention volume estimated at over 40 million m<sup>3</sup>, assuming a managed inundation depth of 0.5 m during peak flows. This substantial storage capacity functions as a pivotal buffer, with the capacity to attenuate downstream flood peaks and thereby reduce the hydraulic load on dike systems.

From an ecological standpoint, the restoration metrics are equally compelling. The intervention area directly supports the Prut River corridor, a critical migration route hosting 225 identified bird species (representing 60% of Romania's total avifauna). Specifically, the restoration targets the conservation status of 37 species listed in Annex I of the Birds Directive and 9 globally endangered species identified in the local ROSPA0042 and ROSCI0213 Natura 2000 sites [19].

Moreover, the restoration metrics extend well beyond the avian value, as the re-establishment of lateral connectivity is crucial for broader aquatic and terrestrial biodiversity. The projected sites within the embanked area of Trifești Sculeni targets the conservation of 5 specific Natura 2000 habitat types, transitioning land use from monoculture to diverse hygrophilous communities. This revitalization of backwaters (japșe) provides critical spawning grounds for protected fish species such as the Sterlet (*Acipenser ruthenus*) and the Weatherfish (*Misgurnus fossilis*). Furthermore, the expanded wetland network secures the habitat for key indicator species listed in the Habitats Directive, including the European pond turtle (*Emys orbicularis*) and mammals requiring strict protection such as the Eurasian otter (*Lutra lutra*), thereby restoring the functional integrity of the local trophic pyramid [19].

Such projects do more than simply create aesthetically pleasing landscapes or isolated habitats; they are designed to re-establish a suite of critical ecosystem services. The restored floodplain can once again serve as a natural storage area for floodwaters, attenuating flood peaks and reducing downstream risk, a concept now famously championed in the Netherlands under the “Room for the River” (Ruimte voor de Rivier) program. This national-scale initiative has moved away from simply raising dikes and instead focuses on strategically creating flood bypasses and lowering floodplains to give the Rhine and Meuse rivers more space, thereby increasing safety while simultaneously creating valuable natural areas [60]. Furthermore, the revitalized wetlands within the Trifești-Sculeni polder are designed to act as biological filters, improving water quality by processing agricultural runoff and trapping sediments before they reach the main river channel, directly supporting the conservation goals of the local Natura 2000 sites.

This approach is guided by a clear and pragmatic distinction between restoration and rehabilitation, as outlined in the review of environmental planning concepts [17]. True ecological restoration is the ambitious process of returning a system to its original, pristine state, a goal pursued in large-scale projects like the landmark re-meandering of the Skjern River in Denmark. There, a straightened, channelized river was returned to its original sinuous course, successfully restoring vast wetland habitats for migratory birds and improving water quality entering the North Sea [61,62]. However, in many heavily modified and populated landscapes, complete restoration is not feasible. In these cases, rehabilitation becomes the objective: a more pragmatic goal where a new, functional, and resilient semi-natural ecosystem is created [63].

The Trifești-Sculeni project is a quintessential example of rehabilitation; it does not remove the primary flood protection embankments but works within them to create a controlled, managed wetland system that balances ecological needs with existing land use and safety requirements. By using natural materials like wood and stone and by strategically allowing the river a designated “space for freedom” to evolve, these solutions

are inherently more resilient and adaptable to climate change, providing a host of co-benefits including enhanced biodiversity, carbon sequestration in wetland soils, and new opportunities for eco-tourism and recreation.

Moreover, the observed synergy is also evident in socio-economic indicators. The transition from a monoculture of arable crops to a mixed-use wetland landscape has been demonstrated to unlock economic potential through sustainable fisheries and eco-tourism. A number of restoration initiatives in the Danube basin have demonstrated that the economic value of ecosystem services, particularly nutrient cycling (water purification) and recreation, can exceed that of conventional agricultural production by a factor of 2 to 3. This validates the economic viability of the nature-based solution approach [64].

### 3.2. Advanced Monitoring and Data Acquisition: The Sensory System of Water Management

Effective management of complex water systems is impossible without a robust, real-time understanding of their dynamic state. This requires a sophisticated “sensory system” composed of advanced monitoring and data acquisition technologies, which forms the empirical backbone of any modern management strategy. The traditional approach of sparse, infrequent manual sampling—while still useful for certain parameters—is being rapidly superseded by networks of permanent and mobile sensors that provide high-frequency, actionable data. In surface water management, this shift is evident in the reliance on automated gauging stations that provide continuous time-series data on flow and level. This type of data, such as the hourly hydrographs from the Ungheni station used for calibrating the hydrodynamic models of the Prut and Bahlui Rivers [19,65], is the fundamental input for any credible flood or water quality simulation. This is now being augmented by in situ water quality sondes that can provide real-time data on key indicators like temperature, dissolved metals, and suspended solids, enabling early warning systems for pollution events, a practice being widely adopted in sensitive catchments like the River Thames basin in the UK [66].

Within groundwater systems, the “sensory network” consists of dedicated observation wells equipped with pressure transducers (dataloggers). These devices provide the high-resolution piezometric data necessary to track the aquifer’s response to pumping and recharge events. This was the exact methodology used to gather the calibration data for the Gherăești-Bacău wellfield model, where measured heads from multiple observation wells were used to validate the accuracy of the MODFLOW simulation, achieving a very low total error of 0.051 m [36]. The true revolution in monitoring, however, is occurring within the urban distribution networks themselves. The widespread implementation of Supervisory Control and Data Acquisition (SCADA) systems provides operators with a centralized, real-time dashboard of the entire system’s performance, from reservoir levels to pump statuses.

This is further enhanced by the strategic deployment of field-based sensors. As detailed in the Iași network study [48], the combination of permanently installed electromagnetic flowmeters at the inlets of District Metered Areas (DMAs) and portable MultiLog data loggers for pressure measurements provides an unprecedented, granular view of the network’s hydraulic behavior. This continuous stream of data, often collected at 15 min intervals, is the lifeblood of modern utility management. It moves operations from a reactive “break-fix” model to a proactive, data-driven one. It allows for the rapid identification of anomalies, such as the sudden increase in minimum night flow that signals a new leak, and provides the empirical basis for calibrating the hydraulic models that form the core of a “digital twin.” Furthermore, this data serves as the direct input for smart control systems that optimize network performance. Without this foundation of high-quality, high-frequency data, both predictive modeling and smart control would be operating blind,

making advanced monitoring an indispensable tool in the global transition towards “Smart Water” networks.

### 3.3. Predictive Modeling: The Brain of Proactive Management

Once a steady stream of data from the sensory network is established, it can be used to power the “brain” of modern water management: predictive numerical modeling. These sophisticated software tools allow engineers and planners to construct a “digital twin”—a dynamic virtual replica of a physical water system that is continuously updated with real-world data. The development and calibration of such a model enable a crucial shift from reactive problem-solving, which addresses failures only after they occur, to proactive, scenario-based planning that can anticipate and mitigate future risks. The suite of case studies mentioned in this paper provides a comprehensive demonstration of this capability across the entire urban water cycle.

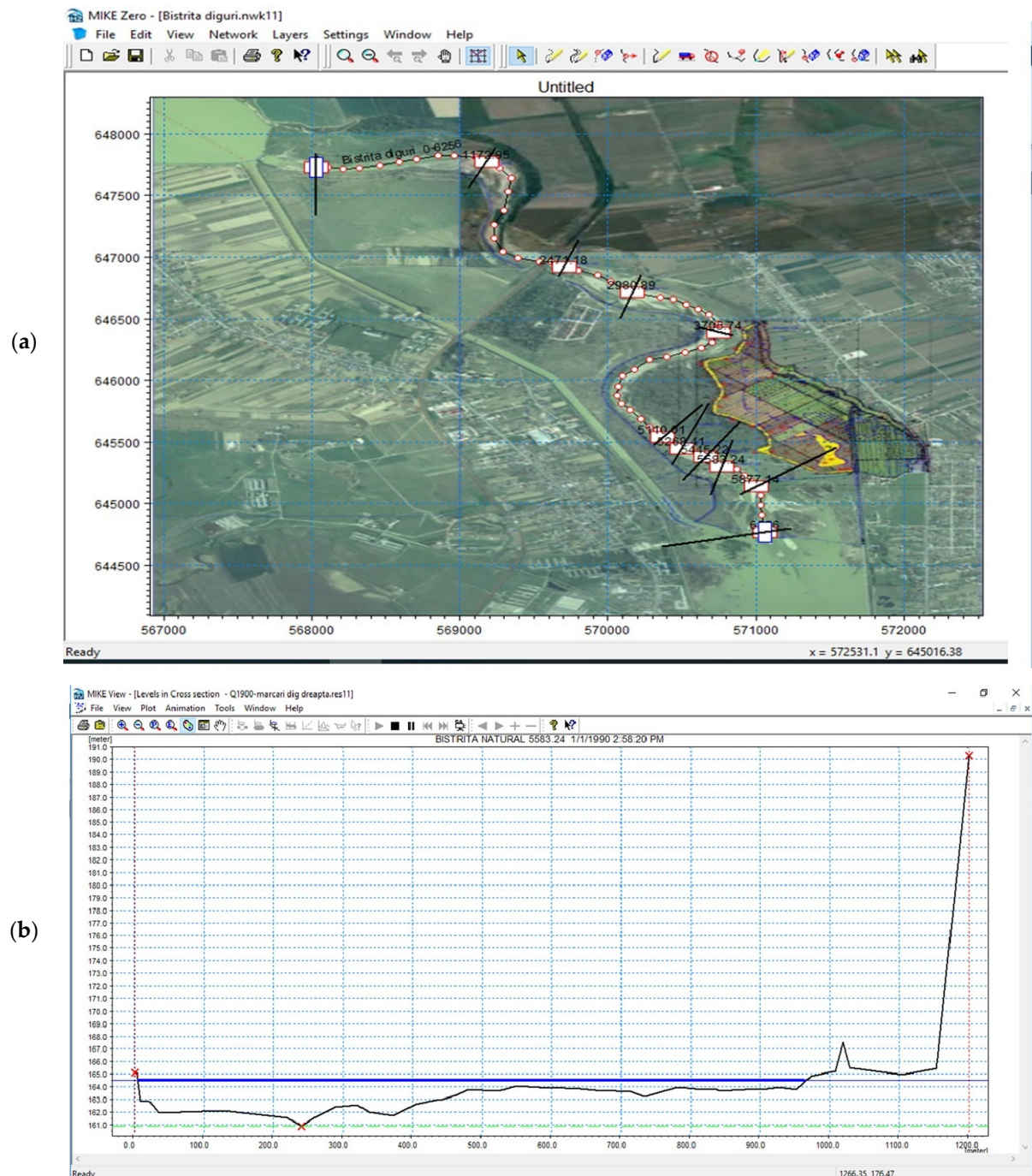
For surface water systems, 1D hydrodynamic models based on the numerical solution of the Saint-Venant equations [67] are the industry standard for simulating flood wave propagation. By discretizing a river into a series of cross-sections and solving for flow and water level over time, these models can accurately predict the impacts of different physical interventions.

This capability is essential for evaluating the effectiveness of flood mitigation strategies, from traditional embankments to nature-based solutions like floodplain restoration, before committing to costly construction. This same hydrodynamic framework forms the transport engine for water quality models. As demonstrated in the MIKE 11 ECO Lab application for the Bahlui River [64], by coupling the hydrodynamics with biogeochemical process modules (e.g., for BOD decay and reaeration), it becomes possible to diagnose pollution hotspots and forecast the downstream effects of potential remediation efforts, such as upgrading a wastewater treatment plant. This type of modeling was famously used in the multi-decade cleanup of Chesapeake Bay in the United States to set Total Maximum Daily Loads (TMDLs) for nutrients from its vast, multi-state watershed [68].

In the subsurface realm, hydrogeological models like the industry-standard MODFLOW [36,43] solve the groundwater flow equation to simulate the movement of water through porous media. The development of a calibrated model for the Gherăești-Bacău wellfield, which accurately replicated observed piezometric levels, provided a robust tool for predictive analysis (Figure 4).

It allowed for a scientifically defensible assessment of the potential impact of a new recreational lake, moving the decision-making process from one of speculation to one of quantitative risk assessment. Such models are indispensable for defining wellhead protection zones, managing saltwater intrusion in coastal aquifers, and planning for the sustainable development of groundwater resources.

Finally, within the engineered environment, hydraulic network models like MIKE URBAN [48] provide a complete representation of a city’s water distribution system. By incorporating data on pipe diameters, materials, pump curves, and consumer demand patterns, these models can simulate pressure and flow throughout a complex network under various operational conditions. This allows utilities to identify hydraulic bottlenecks, size new pipes, plan for flushing programs, and, critically, to strategically target areas for pressure management interventions to reduce water losses. Large utilities like Thames Water in London rely on continuously updated, “all-mains” models as the core of their operational and strategic planning [69]. These models cannot predict the future with certainty. However, they are essential tools for understanding complex system dynamics, quantifying risks, and guiding scientifically informed decisions about the future of water resources.



**Figure 4.** Screenshots from the hydrogeological modeling software showing (a) the location of cross-sections and (b) the simulated water surface elevation in cross-section P15 (at  $Q = 1900 \text{ m}^3/\text{s}$ ), used for the development and calibration of the numerical model (view from south to north).

### 3.4. Smart Network Control: Optimizing the Final Mile

The final tool in this integrated set addresses the operational efficiency of the engineered infrastructure itself, moving from strategic planning to tactical, real-time control. While predictive modeling provides the high-level insight needed to design and reconfigure the system, smart control systems provide the automated, minute-by-minute optimization required to manage a complex distribution network efficiently. The most powerful and widely adopted application of this technology is Active Pressure Management, a proven strategy for tackling the persistent challenge of Non-Revenue Water (NRW) [70]. Traditional systems are typically operated at a fixed, high pressure designed to satisfy consumer

demand during peak hours. This means that for the majority of the day, particularly during low-demand overnight periods, the network is subjected to excessive and unnecessary pressure, which stresses aging pipes and maximizes the rate of water loss from existing leaks.

Smart control systems are designed to break this inefficient cycle. The case study in the Iași metropolitan area provides a clear demonstration of this technology in action [71]. The implementation of the Pegasus 2 system, a modern pressure controller, coupled with an automatic control valve and real-time sensors, allowed for a shift from a static to a dynamic pressure regime [48]. The “before” data from this study clearly shows the classic problem: as the flow (demand) dropped to near zero during the night, the downstream pressure remained consistently high. The “after” data, with the smart system activated, illustrates a dramatic improvement. The system, using real-time flow data as its input, intelligently modulated the valve to reduce and stabilize the downstream pressure precisely during the low-demand period, while still ensuring adequate pressure was available as demand increased in the morning. This approach is a form of “soft engineering” applied to a hard infrastructure system: instead of relying solely on costly and disruptive pipe replacement, it uses intelligent control to extend the life of existing assets and dramatically improve operational efficiency. The underlying principle is the well-established FAVRAD (Fixed and Variable Area Discharges) concept, which recognizes that the flow rate from a leak is directly proportional to the pressure raised to a certain power (the leakage exponent) [72]. Therefore, even a small reduction in pressure can yield a significant reduction in leakage.

Water utilities in cities like Singapore and Sydney have implemented advanced pressure management across their entire networks, creating hundreds of dynamically controlled pressure zones. These “smart water grids” have successfully reduced leakage rates to world-leading lows, demonstrating that this technology is not just an incremental improvement but a transformative one [73]. It not only saves vast quantities of treated water and reduces the energy costs associated with pumping, but it also lowers the frequency of new pipe bursts by reducing mechanical stress, thereby increasing the overall resilience of the network. This makes smart control an indispensable tool for any modern water utility seeking to become more sustainable, efficient, and cost-effective.

## 4. Synthesis: Developing an Integrated Urban Water Management (IUWM) Framework

### 4.1. The River-Aquifer-Network Continuum: A Unified System View

The first and most critical step towards an integrated approach is a fundamental conceptual shift: abandoning the traditional, fragmented view of water systems and embracing the reality of a single, dynamic River-Aquifer-Network Continuum [74]. This perspective recognizes that surface water, groundwater, and engineered distribution systems are not isolated components to be managed in silos but are inextricably linked through a continuous flux of water, energy, and contaminants. The case studies synthesized in this paper demonstrate these profound interdependencies with undeniable clarity.

The interface between surface and groundwater, often simplified in management plans, is in fact a highly dynamic two-way street. The biochemical health of a river like the Bahlui, which exhibits severe organic pollution and a pronounced dissolved oxygen sag, directly determines the quality of the water that may be induced to recharge a nearby alluvial aquifer [75]. The quantitative stress placed on that aquifer by a wellfield, such as the 190 L/s extraction at the Gherăești-Bacău front, can reverse natural hydraulic gradients, pulling river water into the subsurface [36]. This induced infiltration, a critical process quantified in the hydrogeological model, transforms the riverbank from a natural filter into

a direct conduit, shrinking the travel time for surface water pollutants to reach drinking water wells.

This tight coupling is a globally recognized management challenge, famously highlighted in the management of the Platte River basin in the U.S., where the legal and physical links between groundwater pumping and surface water rights have been the subject of decades of intense scientific study and litigation [76].

The volume of reliable, high-quality water that can be sustainably extracted from this coupled river-aquifer system ultimately dictates the raw water supply available to the urban distribution network. This continuum extends even to the failures and inefficiencies within the system. Leaks from aging water mains—a significant problem in the high-pressure Iași network [48]—are not just a loss of a treated product. This exfiltrating water, often carrying disinfectant byproducts, contributes to a form of artificial, and sometimes contaminated, groundwater recharge known as the “urban aquifer.”

In cities like London, leakage from the distribution network is now a major component of the groundwater budget. Conversely, during low-pressure events, contaminated groundwater can infiltrate the pipes, posing a significant public health risk [77].

At the other end of the cycle, the very flood control structures designed to protect cities, such as the channelization documented on the Olt and Prut rivers [17], are a primary cause of the degradation of the surface water sources they were meant to tame. A decision made in one part of this continuum invariably creates ripples—hydraulic, chemical, and ecological—that are felt throughout the others. Therefore, any effective management strategy must operate from the understanding that the river, the aquifer, and the network are not separate problems, but simply different stages in a single, continuous, and powerfully interconnected urban water system.

#### 4.2. *A Proposed Framework for Action: Diagnose, Prescribe, Optimize*

Building upon the unified continuum view, a purely conceptual understanding is insufficient; it must be translated into a practical, iterative framework for action. We propose a three-stage process—Diagnose, Prescribe, and Optimize—that guides water managers from problem identification to sustainable operation by integrating the modern toolbox of solutions into a logical and powerful workflow.

1. **Diagnose**—Building the System-Wide Digital Twin: The foundational stage of any modern management intervention is a deep, quantitative understanding of the system’s current state. This moves beyond treating isolated symptoms (e.g., a localized flood or a pipe burst) to identifying the root causes of systemic dysfunction. This is achieved by creating a comprehensive, data-driven “digital twin” of the entire urban water system, powered by the tools of advanced monitoring and predictive modeling. This involves developing and calibrating a suite of interconnected models: a hydrodynamic model to understand flood risk, as was done for the Prut River; a hydrogeological model to assess aquifer stress and vulnerability, as demonstrated for the Gherăești-Bacău wellfield; and a hydraulic network model to pinpoint inefficiencies, as applied to the Iași distribution system. By integrating these components, managers can accurately map the River-Aquifer-Network continuum, identify critical points of failure, and run “what-if” scenarios to test the sensitivity of the system to various stressors. This diagnostic engine provides the scientific basis for all subsequent actions.
2. **Prescribe**—Implementing Foundational, Nature-Based Solutions: Based on the system-wide diagnosis, the second stage involves the strategic implementation of large-scale, often nature-based, solutions designed to restore the fundamental health and resilience of the natural components of the system. This is the stage for “big picture,” foundational interventions that address the systemic failures identified in

the diagnostic phase. A prime example is the proposed rehabilitation of the Trifești-Sculeni floodplain, which prescribes the re-establishment of over 8000 hectares of functional wetlands. This is not merely an environmental project; it is a strategic hydraulic intervention designed to restore natural flood attenuation and improve regional water quality. This approach aligns with global best practices, such as the massive “Making Space for Water” initiative in the UK, which prioritizes floodplain reconnection and managed realignment of coastal defenses over the construction of ever-higher concrete walls [78]. These prescriptions act as a form of preventative medicine, healing the core of the water system rather than just managing its symptoms.

3. **Optimize**—Fine-Tuning Engineered Systems with Smart Technology: The final stage focuses on the continuous, real-time improvement of the engineered components of the system, ensuring they operate with maximum efficiency and minimal environmental impact. Once the foundational health of the natural system is addressed through prescription, smart technologies are deployed to fine-tune the performance of the hard infrastructure. The implementation of Active Pressure Management in the Iași network, which demonstrated a clear ability to reduce and stabilize system pressures during low-demand periods, is a perfect example of optimization. This not only reduces water losses and saves energy but also lowers the physical stress on aging pipes, extending the life of the infrastructure. This principle of dynamic optimization is the core of “smart water grids” being developed in cities like Singapore, where thousands of sensors and automated valves work in concert to minimize leakage and ensure a resilient supply.

The theoretical innovation of the DPO framework lies in its shift from a descriptive IUWM policy approach to a prescriptive technological workflow. Unlike existing IUWM models that broadly advocate for integration, DPO mandates a strict, sequential hierarchy: the digital diagnosis must define the boundary conditions for the nature-based prescription, which in turn dictates the operational limits for the smart optimization. For the specific challenge of the ‘river-aquifer-network’ continuum, this framework offers a unique advantage by quantifying cross-system feedback loops. Traditionally, river restoration and distribution network management are treated as independent engineering silos; the DPO framework forces these domains into a single analytical pipeline, ensuring that enhancements in the natural system (e.g., increased aquifer recharge through floodplain renaturation) are directly utilized to optimize the performance of the engineered infrastructure.

Crucially, this framework is not a linear, one-time process but a continuous, adaptive management cycle. The results of optimization and the ongoing performance of prescribed solutions are constantly fed back into diagnostic models through advanced monitoring. This allows for the continuous refinement of the system’s digital twin, leading to better-informed prescriptions and more effective optimization over time, creating a virtuous cycle of improvement.

It is important to distinguish the DPO framework from classic adaptive management cycles. While traditional models offer a generic procedural loop (e.g., Plan-Do-Check-Act), the DPO framework provides a targeted technological roadmap tailored specifically for the River-Aquifer-Network continuum. Its distinction lies in mandating a specific class of tools for each phase: it requires that Diagnosis be driven by integrated numerical modeling (Digital Twins), Prescription must prioritize Nature-Based Solutions (NBSs) to heal fundamental ecosystem functions, and Optimization must employ smart sensor technologies to fine-tune gray infrastructure.

To transition this framework from a descriptive concept into a prospective planning tool, its success must be evaluated against specific operational criteria. Based on the dynam-

ics analyzed in our regional case studies, we propose that the prospective implementation of the DPO framework can be measured by three primary criteria:

- Diagnostic Fidelity (the proven ability of the integrated models to accurately replicate historical extremes, such as achieving minimal error margins in piezometric or flood level simulations);
- Prescriptive Synergy (the quantifiable recovery of lost ecosystem services, measured by regained flood storage volumes and the return of protected indicator species within the rehabilitated zones);
- Optimization Efficiency (verifiable reductions in nocturnal pressure variances and subsequent, measurable decreases in Non-Revenue Water percentages).

The applicability of the DPO framework extends to any urbanizing landscape contending with infrastructure decay and climatic extremes, transcending the specific Eastern European case studies presented here. Operational boundaries for this framework are primarily defined by data availability. The ‘Diagnose’ phase relies on a baseline of digital monitoring; consequently, in data-poor regions, this phase cannot be fully realized without preliminary investment in sensory infrastructure, such as SCADA systems and gauging stations. Furthermore, the successful transition from prescription to optimization necessitates a high degree of cross-institutional data sharing, a factor that remains a significant governance boundary in many developing urban contexts.

By focusing on these specific, measurable outcomes, the DPO framework offers a practical and accountable pathway for urban water resilience.

#### 4.3. Overcoming Fragmentation: Institutional and Governance Challenges

While the technical tools for integrated management are increasingly available and proven, their successful implementation is often hindered by a more persistent and deeply entrenched form of fragmentation: institutional and governance silos. The technical reality of a River-Aquifer-Network continuum often collides with an administrative landscape that is artificially and rigidly divided [79]. Historically, water management responsibilities have been segregated among separate, often uncoordinated, agencies, each with its own specific mandate and jurisdiction [80].

This is clearly reflected in the context of the mentioned case studies. A national or regional river basin authority, such as the Prut-Bârlad Water Basin Administration, is typically responsible for flood control, surface water quality monitoring, and the management of large hydraulic structures. A separate municipal or regional utility, like the operator in Iași or Bacău, is tasked with groundwater extraction, water treatment, and the operation and maintenance of the distribution network.

Meanwhile, municipal departments for urban planning and environmental protection are responsible for land-use zoning and stormwater management, often with little to no direct coordination with the water utility or river authority. These organizations frequently operate under conflicting mandates, compete for separate budgets, and are driven by different regulatory requirements (e.g., the EU Water Framework Directive for the river authority vs. drinking water standards for the utility) [81,82]. This institutional separation creates significant barriers to the kind of holistic planning advocated for in this paper, making it difficult to implement multi-benefit projects that span jurisdictional boundaries.

For an integrated framework to succeed, this institutional fragmentation must be overcome. This requires a conscious move away from top-down, single-objective management towards new models of collaborative and polycentric governance that bring all relevant stakeholders to the table.

Successful international examples provide a blueprint for this transition. The integrated water management associations of Germany, such as the Emscher-genossenschaft

in the Ruhr region, are a prime example [83]. This century-old public body manages the entire water cycle for a whole river basin—from wastewater treatment to flood control and ecological restoration—funded by contributions from all polluters and beneficiaries, thus internalizing environmental costs and aligning stakeholder interests. More recently, the establishment of multi-stakeholder Catchment Partnerships across England, driven by the EU Water Framework Directive, brings together water companies, environmental agencies, local authorities, and NGOs to co-develop and implement basin-scale management plans [84].

Key enablers for this transition, which are universally applicable, include:

1. The creation of shared data and modeling platforms, where monitoring data and the “digital twin” of the water system are accessible to all parties, creating a common, science-based understanding of the problems;
2. The development of integrated, basin-scale management plans that are co-authored by all relevant agencies and explicitly align the objectives of flood risk, water supply, and ecological health;
3. The crucial alignment of funding mechanisms to prioritize and support multi-benefit projects, such as a floodplain restoration that can simultaneously claim funding from flood defense, environmental improvement, and public recreation budgets.

Without a deliberate and sustained effort to dismantle these institutional barriers and foster a culture of cross-jurisdictional collaboration, even the most advanced technical solutions will remain isolated interventions, and the full, synergistic potential of integrated water management will remain unrealized.

#### 4.4. Case Study Illustration: The Iași-Bacău Region as a Microcosm

The body of work synthesized in this paper, focusing on the Iași-Bacău region of Eastern Romania, serves as a powerful real-world microcosm of the proposed integrated framework. While these individual research projects were not initially conceived as part of a single, overarching IUWM strategy, their collective evidence provides a compelling, post hoc validation of the framework’s logic. When viewed together, they demonstrate not only that the problems of fragmentation are real and present in this region but also that all the necessary technical components for implementing the **Diagnose-Prescribe-Optimize** cycle are available, tested, and applicable within this specific context.

However, the imperative for adopting this integrated framework extends beyond theoretical consistency; it is driven by the severe historical and evolving flood risks that characterize the Iași-Bacău region. These urban centers have long battled against the destructive force of water, evolving from the historical struggle against catastrophic riverine floods to the modern challenge of pluvial flash floods caused by rapid urbanization and climate variability. The magnitude of this challenge, which defies simple static solutions, is documented in Table 1.

Precise instrumental data (e.g., exact peak discharges or calculated return periods) are unavailable for the earliest historical entries, but the phenomenological records provide a clear typological timeline. The synthesis of major flood events over the last two centuries reveals a critical evolution in the hazard profile. Even though the massive hydrotechnical investments of the mid-20th century successfully mitigated the frequency of catastrophic, large-basin riverine floods (such as the devastating Siret flows of 1970 and 1991), the vulnerability has not disappeared, but rather migrated. As the table illustrates through the changing nature of the impacts—from the destruction of riparian mills to the paralysis of urban underpasses—the region now faces a dual threat. The static “gray infrastructure” is increasingly being bypassed by high-intensity, short-duration pluvial events concentrated over highly impermeable urban surfaces (as seen in the frequent events in Iași post-2010).

This transition demonstrates that relying solely on static defensive structures is insufficient for current climatic realities.

**Table 1.** Chronological synthesis of major hydro-meteorological events and flood impacts in the Iași and Bacău urban agglomerations (19th Century–Present).

| Urban Center | Water Body/Source         | Event Year  | Hydro-Meteorological Parameters ( $Q_{\max}/P$ ) *      | Hydromorphological Context & Socio-Economic Impact                                                                                                                                                                                                                     |
|--------------|---------------------------|-------------|---------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Bacău        | Bistrița & Siret Rivers   | 1837        | Not recorded (Historical high magnitude)                | “The Great Deluge”. Historical chronicles record the hydraulic merging of the Bistrița and Siret floodplains, creating a unified water body. Total destruction of wooden hydraulic structures (mills) and bridges.                                                     |
|              | Bistrița River            | 1893        | Not recorded (High return period event)                 | Catastrophic riverine flood. Severe impact on the riparian residential zones. High mortality rate recorded among the raft workers (plutași), indicating high flow velocities and debris transport                                                                      |
|              | Bistrița River            | 1948        | Not recorded                                            | Pre-regulation era flood. The last major event before the construction of the Bicaz hydroelectric complex. Inundation of the central-low areas and Gherăești Park. This event catalyzed the implementation of the national electrification and embankment plan.        |
|              | Siret River               | 1970 (May)  | $Q_{\max} > 2500 \text{ m}^3/\text{s}$                  | National hydrological disaster. Exceedance of defense thresholds. Partial isolation of the municipality. Severe inundation of peripheral districts (Letea, Șerbănești) and destruction of transportation infrastructure (bridges).                                     |
|              | Siret River               | 1991 (July) | $Q_{\max} > 3000 \text{ m}^3/\text{s}$                  | Hydraulic infrastructure failure. The catastrophic failure of the Belci dam led to a surge wave exceeding the design capacity of downstream defenses. Massive destruction of energy and road infrastructure; widespread inundation of peri-urban zones.                |
|              | Siret River               | 2005 (July) | $Q_{\max} > 2800 \text{ m}^3/\text{s}$                  | Historical riverine flood. Prolonged hydraulic stress on the flood defense dikes. Inundation of agricultural lands and settlements in the Holt/Letea Veche sector due to embankment overtopping or seepage.                                                            |
| Iași         | Siret River               | 2010        | $Q_{\max} > 2400 \text{ m}^3/\text{s}$                  | High flood risk. Critical water levels threatened dike stability. Secondary impact on the municipal water supply system due to extreme turbidity levels preventing treatment.                                                                                          |
|              | Bahlui River              | 1871        | Not recorded (High return period event)                 | Floodplain activation. The floodwaters reached the embankment of the newly constructed railway, effectively isolating the city. The Podu Roș area reverted to a lacustrine state, highlighting the vulnerability of the low-lying urban expansion.                     |
|              | Bahlui River              | 1932        | Not recorded (Historical high magnitude)                | Critical design event. The most severe flood in modern history, serving as the reference for subsequent hydro-technical regularization. Hydraulic coupling of Bahlui and Nicolina rivers occurred. Water depths exceeded 2.0 m in the Podu Roș district.               |
|              | Nicolina River/Pluvial    | 2013        | $P \approx 70 \text{ L}/\text{m}^2$ (in 2 h)            | Urban flash flood. The Nicolina river reached danger levels. The drainage capacity of road underpasses (e.g., Galata) was exceeded, leading to the paralysis of urban traffic and inundation of critical transport nodes                                               |
|              | Pluvial (Sewerage Runoff) | 2018        | $P \approx 60\text{--}80 \text{ L}/\text{m}^2$          | Sewerage system capacity exceedance. High-intensity rainfall event over impervious urban surfaces generated rapid surface runoff. Widespread flooding of basements and streets in the central and Canta districts due to hydraulic overload of the collection network. |
|              | Pluvial (Sewerage Runoff) | 2021        | $P \approx 50 \text{ L}/\text{m}^2$ (Torrential bursts) | Urban hydrologic stress. Blockage of public transport networks. Significant material damage (vehicles swept by flow, pavement delamination) in the Podu Roș and Railway Station areas, confirming the shift from riverine to pluvial risk dominance.                   |

\* Note:  $Q_{\max}$  = Maximum discharge; P = Precipitation intensity.

It is also important to note that the temporal gap between the last recorded events in Table 1 and the present (spring 2026) reflects a significant period of climatic shift. Between 2021 and 2025, North-East Romania was characterized by a severe and persistent pedological drought, resulting in a period of hydrological inactivity regarding flood events. Consequently, no major hydro-meteorological events with significant inundation impacts occurred during these years that warranted inclusion in this historical synthesis. This further underscores the extreme climate variability inherent to the region, where the management framework must be resilient enough to handle both sudden pluvial surges and prolonged periods of water scarcity.

Therefore, this persistent and morphing risk validates the logic of the proposed framework: the “old” riverine risks require constant Diagnosis through modeling, while the “new” pluvial risks demand the Optimization of existing networks and the Prescription of nature-based buffers.

In the context of the DPO framework, Table 1 acts as the empirical foundation for the “Diagnose” stage. Rather than serving as a static archive, these historical records provide the essential ‘stress-test’ scenarios and historical boundary conditions required to calibrate and validate the regional Digital Twins. By identifying the magnitude and typology of past extremes—such as the hydraulic coupling of the Bahlui and Nicolina rivers in 1932—the framework allows modelers to define the necessary sensitivity parameters for predictive simulations. This ensures that the diagnostic models are not just theoretically sound but are grounded in the documented physical limits of the region’s hydrological system.

Consequently, this persistent risk validates the logic of the proposed framework: the ‘old’ risks require constant Diagnosis through modeling (to understand the new flow regimes), while the ‘new’ pluvial risks demand the Optimization of existing networks (to handle rapid run-off) and the Prescription of nature-based buffers. Thus, the history of flooding in Iași and Bacău serves not just as a record of damage, but as the primary argument for transitioning to the dynamic, integrated management model detailed below.

The Diagnose stage, the creation of a system-wide digital understanding, is clearly represented by the suite of advanced numerical models developed for the region. The state of the surface water continuum was quantified through the MIKE 11 hydrodynamic and water quality model of the Bahlui River, which successfully identified critical zones of organic pollution and oxygen depletion [85]. The subsurface component was characterized by the MODFLOW model of the Gherăești-Bacău aquifer, which simulated the complex interactions between the Bistrița River and the wellfield, quantifying the 190 L/s extraction stress [36,43]. Finally, the intricate dynamics of the engineered infrastructure were captured by the MIKE URBAN hydraulic model of the Iași distribution network, a system spanning 1426 km of pipes [48]. Collectively, these models form the constituent parts of a regional “digital twin,” providing a deep, multi-faceted diagnosis of the water system’s state.

The Prescribe stage, which calls for foundational, nature-based interventions, is epitomized by the detailed engineering proposal for the renaturation of the Trifești-Sculeni floodplain [8,19,86]. This project is a clear prescription aimed at healing a core part of the regional water system. By proposing to re-establish connectivity and provide a calculated flushing flow, the project aims to restore the fundamental ecosystem services of flood attenuation and natural water purification across a vast area, directly addressing the types of hydromorphological and biochemical degradation documented elsewhere in the region. This aligns perfectly with the international shift towards prescribing large-scale, nature-based solutions as a primary response to systemic environmental problems.

Finally, the Optimize stage is demonstrated in practice through the successful implementation and testing of the Pegasus 2 active pressure control system within the Iași network [48]. This is a textbook example of optimization: taking an existing, high-stress

engineered system and using smart, real-time technology to fine-tune its performance. The clear “before and after” results, showing a marked reduction in nocturnal pressures, provide tangible proof of the benefits of moving from a static to a dynamic operational philosophy. This emergent, “bottom-up” application of the Diagnose-Prescribe-Optimize framework within the Iași-Bacău region demonstrates that integrated water management is not merely a theoretical ideal. It is a practical and achievable goal, built upon a foundation of specific, proven technical capabilities that are ready to be scaled and formally integrated into a cohesive, forward-looking strategy for regional water security and resilience.

Furthermore, the conditions defining the Iași Bacău region render these conclusions highly generalizable to other medium-sized urban agglomerations across Eastern Europe and the Balkans. As documented in comparative studies of post-socialist urban transitions [87–89], these cities share a distinct, systemic hydro-technical typology characterized by the following attributes:

- (1) A legacy of extensive 20th-century river channelization for flood defense purposes, which disrupted natural hydromorphology [90,91];
- (2) A highly centralized but deteriorating water infrastructure that suffers from decades of deferred maintenance, resulting in the high regional NRW rates (often exceeding 40%) consistently reported by the Danube Water Program [92];
- (3) A rapid, post-1990 peri-urban areas development that outpaces drainage capacity of the drainage systems to cope with this urban expansion [93].

Therefore, the Diagnose-Prescribe-Optimize framework and the specific technical solutions evaluated in this study, including active pressure control and flood plain rehabilitation, are directly transferable to similar urban contexts facing the dual challenge of climate adaptation and infrastructure modernization.

## 5. Conclusions and Recommendation

The evidence synthesized in this research leads to an unequivocal conclusion: the fragmented, single-objective engineering paradigms of the past are no longer adequate for managing the complex water challenges of the 21st century. Based on the regional case studies analyzed, the primary outcomes of this research are summarized as follows:

- **The River-Aquifer-Pipe Network Continuum:** The primary outcome of this synthesis is the validation of the urban water system as an integrated continuum. Treating these components in isolation ignores the mutually reinforcing feedback loops that propagate degradation across the entire system.
- **Hydromorphological and Biochemical Collapse:** River channelization (e.g., the Prut and Olt rivers) directly exacerbates downstream flood peaks and cripples natural self-purification capacities, leading to severe biochemical distress, evidenced by critical DO sags and high BOD levels (e.g., the Bahlui River).
- **Groundwater Vulnerability:** Intensive urban groundwater extraction (e.g., 190 L/s at the Gherăești-Bacău wellfield) significantly alters regional hydrogeology, potentially inducing surface water infiltration and increasing the contamination risk for strategic reserves.
- **Infrastructure Failure:** The cascading systemic stress culminates in aging distribution networks (e.g., the Iași system), where the necessity for high-pressure operations drives chronic and costly Non-Revenue Water (NRW) losses.
- **The DPO Framework:** To address these deeply interconnected problems, this paper proposes the Diagnose-Prescribe-Optimize (DPO) framework, operationalizing the Integrated Urban Water Management (IUWM) approach into a practical roadmap.
- **Integrated Solutions:** The synthesis proves that a resilient urban water system requires a multi-tool approach: deep model-based Diagnosis, the Prescription of founda-

tional Nature-Based Solutions (like the Trifesti-Sculeni floodplain rehabilitation), and the continuous Optimization of existing infrastructure using smart, active pressure control technologies.

Looking ahead, the primary challenge and the most promising avenue for future research lies in moving from a de facto, post hoc integration of these components to a formal, a priori one. The next logical step, mirroring a global trend in urban and environmental engineering, is the development of a true Digital Twin for an entire urban water system. This would involve the formal, dynamic coupling of the individual models presented—linking the output of the MIKE 11 river model as a boundary condition for the MODFLOW aquifer model, whose output (wellfield abstraction) in turn becomes a primary input for the MIKE URBAN network model. Such a fully integrated digital replica, continuously assimilated with real-time data from a comprehensive SCADA and sensor network, would represent the ultimate decision-support tool, a concept being actively pursued in “smart city” initiatives from Singapore to Santander, Spain.

This integrated model would allow managers and policymakers to simulate the full, system-wide consequences of any proposed action or external stressor—from the construction of a new housing development and its impact on runoff and water demand, to the implementation of new agricultural policies affecting nutrient loads, or the cascading impacts of a projected climate change scenario involving prolonged drought followed by an extreme flood event. Building these integrated digital twins is a complex, data-intensive, and interdisciplinary endeavor that will require unprecedented collaboration between the institutional silos discussed previously. However, it represents the clear future of water management. It is the key to navigating the profound uncertainties of the Anthropocene and transforming our cities into truly resilient, water-secure, and sustainable environments.

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