Cyber-resilient smart water management in the Dniester Basin: integrating AI and transboundary infrastructure within EU climate missions

Anatolie Babin
Academy of Economic Studies of Moldova, Chisinau, Republic of Moldova
anatolie.babin@ase.md

Sergiu Tutunaru
Academy of Economic Studies of Moldova, Chisinau, Republic of Moldova
tutunaru@ase.md

Ion Covalenco
National Research and Educational Network of Moldova, Chisinau, Republic of Moldova
ion.covalenco@renam.md

Abstract
This paper aims to explore how cybersecurity can be systemically integrated into smart water management systems in transboundary river basins to support the development of climate-neutral and smart cities. Objectives: This paper aims to explore how cybersecurity can be systematically integrated into smart water management systems in transboundary river basins to support the development of climate-neutral and intelligent cities. It addresses the growing reliance on ICT, including IoT, big data, and artificial intelligence (AI), and the associated cyber risks affecting critical water infrastructure. Prior work: Existing studies highlight the role of digital technologies in smart water management and urban sustainability; however, insufficient attention has been paid to cybersecurity challenges, particularly in cross-border contexts characterized by fragmented data management and complex data exchange. This paper builds upon smart water and smart city research by incorporating cyber resilience and secure data governance principles. Approach: A qualitative case study approach is adopted, focusing on the Dniester River basin as a representative transboundary system. The research combines analysis of institutional frameworks and technological trends with the development of a conceptual model for secure and resilient water management architecture. Results: The study identifies key vulnerabilities, including risks related to data integrity, sensor networks, and communication systems, and demonstrates the necessity of integrating cybersecurity-by-design into digital water infrastructures. A conceptual framework, "EU Green Dniester–Black Sea Corridor," is proposed, combining AI-driven monitoring, secure data exchange, and multi-level administration mechanisms. Implications: The findings are relevant for policymakers, researchers, and practitioners involved in smart cities, environmental management, and critical infrastructure protection, emphasizing the need for coordinated cybersecurity strategies. Value: The paper provides an original interdisciplinary contribution by linking cybersecurity, water management, and EU policy frameworks, and by proposing a novel model for cyber-resilient transboundary water systems.

Keywords: cyber resilience; smart water systems; transboundary governance; data security; critical infrastructure

1. Introduction
Transboundary river basins represent complex socio-ecological and technological systems in which environmental sustainability, economic development, climate adaptation, and geopolitical coordination are deeply interconnected. In the context of accelerating climate change, increasing anthropogenic pressure, and the rapid digitalization of critical infrastructure [1] , effective smart governance [2] of shared water resources requires the integration of advanced digital technologies, cyber-resilient infrastructures, and multi-level

institutional coordination mechanisms [3]. The Dniester River Basin [4], shared by the Republic of Moldova and Ukraine, constitutes one of the most strategically important transboundary freshwater systems in Eastern Europe. The basin supports drinking water supply, agriculture, industrial activities, biodiversity conservation, inland navigation, and regional socio-economic stability. At the same time, the Lower Dniester [5] and the Dniester Estuary [6] are increasingly exposed to hydrological instability, ecosystem degradation (Figure 1), salinity fluctuations, climate-related risks, and growing pressure on water quality and environmental resilience. These challenges are further intensified by fragmented monitoring systems, limited interoperability of digital infrastructures, and insufficient coordination among institutional actors operating across national and regional levels.



Fig. 1. The Low Dniester and Dniester Estuary
Source : https://browser.dataspace.copernicus.eu/

In recent years, the European Union has significantly expanded its strategic framework for sustainable and digital water governance through initiatives such as the Water Framework Directive (WFD)[7], Marine Strategy Framework Directive (MSFD)[8], the European Green Deal[9], the EU Strategy for the Danube Region (EUSDR)[10], Horizon Europe Missions[11], and the development of open-data and digital governance ecosystems. These initiatives promote integrated environmental monitoring, data interoperability, smart infrastructure, and climate-neutral territorial development. Simultaneously, the emergence of technologies such as the Internet of Things (IoT) [12], GeoAI [13], Digital twins [14], cloud computing, and cyber-physical systems has created new opportunities for intelligent water resource management, predictive environmental modeling, and adaptive governance.

However, despite the growing body of research on smart water systems and digital governance, significant gaps remain in the integration of cybersecurity and cyber-resilience into transboundary water management frameworks. Existing studies predominantly focus either on hydrological modeling, environmental monitoring, or smart-city technologies, while comparatively limited attention has been devoted to the cyber-physical vulnerabilities of digital water infrastructures, particularly within politically and institutionally fragmented transboundary regions. Moreover, the governance implications

of integrating AI-driven analytics, digital twins, and open-data ecosystems into cross-border water management architectures remain insufficiently explored in the context of climate adaptation and critical infrastructure protection.

This research addresses these gaps by examining the Dniester Basin as a case study for the development of a cyber-resilient and data-driven transboundary water governance model aligned with European climate and digital transition strategies. The study conceptualizes the integration of IoT-based monitoring systems, GeoAI analytics, digital twin architectures, and multi-level governance mechanisms into a unified framework capable of supporting sustainable, climate-adaptive, and secure management of shared water resources. The article is guided by three interrelated research objectives. First, it analyzes the institutional, technological, and environmental challenges affecting transboundary governance in the Lower Dniester Basin and the Dniester Liman. Second, it identifies key cyber-resilience vulnerabilities associated with sensor networks, data infrastructures, and digital communication systems used in water monitoring and management. Third, it proposes a conceptual framework - the "EU Green Dniester–Black Sea Corridor" [15] - designed to integrate AI-enabled monitoring, cyber-secure data exchange, digital twin modeling, and multi-level transboundary coordination within the broader context of European climate missions and smart territorial development.

Methodologically, the study applies a qualitative case-study approach combining systems analysis, institutional assessment, digital governance analysis, and conceptual modeling of cyber-resilient architectures. The proposed framework is structured around three interconnected layers: (i) the data layer (IoT and geospatial data infrastructures), (ii) the intelligence layer (GeoAI and digital twin analytics), and (iii) the governance layer (multi-level and transboundary coordination mechanisms). This approach enables the integration of technological, environmental, and governance dimensions into a coherent analytical model. The scientific contribution of the article is threefold. First, it advances the conceptual integration of cyber-resilience into smart transboundary water governance. Second, it expands the application of GeoAI and digital twin approaches within climate-adaptive river basin management. Third, it contributes to the emerging interdisciplinary discourse connecting digital governance, environmental sustainability, critical infrastructure protection, and EU climate-transition policies.

From a practical perspective, the study provides a strategic framework for policymakers, regional authorities, research institutions, and international partners seeking to develop interoperable, secure, and climate-resilient digital infrastructures for transboundary river systems. The proposed approach also contributes to the broader discussion on the role of smart and climate-neutral territories in strengthening environmental security and regional cooperation within the Black Sea and Danube macro-regional context [16]. The remainder of the article is structured as follows. Section 2 examines the theoretical and conceptual foundations of digital and cyber-resilient transition in transboundary water governance. Section 3 analyzes the current institutional, technological, and environmental challenges in the Dniester Basin. Section 4 discusses pilot digital initiatives and presents the conceptual GeoAI-enabled Digital Twin [17] architecture. Finally, the concluding sections summarize the main findings and provide policy-oriented recommendations for the development of

cyber-resilient smart water governance systems aligned with European strategies and climate missions.

2. Theoretical and conceptual framework of the digital and cyber-resilient transition in transboundary water governance

The growing complexity of transboundary water governance in the context of climate change, digital transformation, and geopolitical interdependence has intensified the need for integrated theoretical approaches capable of linking environmental monitoring, cyber-resilience, data governance, and multi-level institutional coordination. Contemporary river basin management increasingly depends on cyber-physical infrastructures composed of interconnected sensor networks, geospatial data systems, artificial intelligence (AI), cloud-based platforms, and decision-support architectures. Within this evolving paradigm, water governance is no longer limited to hydrological regulation and environmental protection, but also encompasses digital interoperability, cybersecurity, data sovereignty, and adaptive governance capacities.

The transition toward smart and climate-resilient water management is closely associated with the emergence of cyber-physical environmental systems, where physical ecological processes are continuously monitored, interpreted, and managed through distributed digital infrastructures. In this context, the Internet of Things (IoT) constitutes the foundational technological layer of modern water governance architectures. IoT-based sensor systems enable the continuous acquisition of hydrological, meteorological, ecological, and infrastructural data across geographically distributed river basin environments. Such infrastructures provide real-time monitoring capabilities essential for flood forecasting, drought management, water-quality assessment, and ecosystem protection. From an architectural perspective, IoT infrastructures in smart water systems[18] typically consist of several interconnected layers: (i) the sensing layer, incorporating environmental sensors and monitoring stations; (ii) the communication layer, responsible for secure data transmission; (iii) the data-processing layer, integrating cloud and edge computing infrastructures; and (iv) the analytical and decision-support layer, where AI-based models and predictive systems are deployed. This layered structure enables scalability, interoperability, and operational resilience while facilitating integration with geospatial intelligence and digital twin technologies.

However, the expansion of digital water infrastructures simultaneously increases the exposure of critical environmental systems to cyber threats. Sensor networks, cloud services, communication channels, and decision-support platforms may become vulnerable to unauthorized access, data manipulation, ransomware attacks, and disruptions of operational continuity. Consequently, the concept of cyber-resilience has become increasingly important within environmental governance and critical infrastructure management.

Cyber-resilience extends beyond conventional cybersecurity by emphasizing the capacity of systems not only to resist cyberattacks, but also to maintain operational functionality, recover from disruptions, and adapt to evolving threats under conditions of uncertainty. In the context of transboundary water governance, cyber-resilience includes several

interrelated dimensions: protection of sensor integrity, secure cross-border data exchange, redundancy of communication infrastructures, verification of environmental data authenticity, and institutional coordination in cyber incident response. The integration of cyber-resilience principles into digital water infrastructures is therefore essential for ensuring trust, continuity, and stability within transboundary governance systems.

Simultaneously, the growing availability of geospatial and environmental data has accelerated the development of GeoAI approaches for intelligent environmental governance. GeoAI combines geospatial technologies, machine learning, remote sensing, and spatial analytics to identify patterns, anomalies, and predictive relationships within complex environmental systems. In transboundary river basins, GeoAI enables advanced spatial-temporal modeling of hydrological dynamics, ecosystem changes, pollution diffusion, and climate-related risks.

The application of GeoAI in water governance significantly enhances predictive and adaptive capacities by enabling automated analysis of large-scale environmental datasets. Through machine-learning algorithms and spatial intelligence models, GeoAI can support early warning systems, optimize resource allocation, identify vulnerable ecological zones, and improve scenario-based planning for climate adaptation. Importantly, GeoAI also strengthens evidence-based policymaking by transforming fragmented environmental observations into actionable governance intelligence.

Building upon IoT and GeoAI infrastructures, the concept of the digital twin has emerged as one of the most advanced paradigms in environmental and infrastructural governance. A digital twin represents a dynamic digital replica of a physical system continuously updated through real-time data streams, simulation models, and predictive analytics. In water governance, digital twins enable integrated modeling of hydrological processes, ecological conditions, infrastructural operations, and anthropogenic pressures within a unified cyber-physical environment.

The governance relevance of digital twins extends beyond technical modeling. Digital twins increasingly function as strategic governance platforms capable of integrating scientific knowledge, institutional coordination, and participatory decision-making processes. In transboundary contexts, digital twins can support shared situational awareness among multiple jurisdictions by enabling collaborative visualization of environmental scenarios, risk assessments, and policy alternatives. Such systems facilitate transparency, interoperability, and coordinated responses to environmental and climate-related challenges.

The concept of Digital Twin Governance therefore represents a transition from static monitoring systems toward adaptive and data-driven governance ecosystems. Within this framework, environmental management becomes a continuous process of real-time sensing, predictive analysis, institutional coordination, and strategic adaptation. The integration of digital twins into transboundary governance architectures also aligns with broader European initiatives promoting smart territories, climate-neutral development, and interoperable digital infrastructures. At the institutional level, these technological

transformations require the adoption of multi-level governance approaches capable of coordinating actors operating across local, regional, national, and supranational scales. Multi-level governance theory emphasizes the distributed nature of authority and decision-making in complex policy environments, particularly within transboundary and environmental governance systems. In river basin management, governance effectiveness depends on the ability to integrate municipalities, research institutions, environmental agencies, civil society organizations, and international regulatory frameworks into coherent coordination structures.

The European Union has increasingly promoted multi-level governance mechanisms through initiatives such as the EU Strategy for the Danube Region (EUSDR), the European Green Deal, Horizon Europe Missions, and the Water Framework Directive (WFD). These frameworks encourage integrated territorial governance, cross-border cooperation, open-data ecosystems, and institutional interoperability. The concept of National Adaptation Hubs [19] further reinforces this governance model by linking scientific expertise, local implementation capacities, and climate adaptation policies within interconnected governance networks.

For the Dniester River Basin, multi-level governance is particularly important due to the transboundary nature of the ecosystem and the institutional asymmetries between Moldova and Ukraine. Effective governance requires coordinated monitoring standards, interoperable digital infrastructures, harmonized environmental policies, and secure mechanisms for transboundary data exchange. Moreover, the participation of local communities and municipalities remains essential for ensuring the social legitimacy and operational sustainability of digital environmental governance systems. An equally important dimension of the digital transition concerns the role of open data and geospatial interoperability frameworks. Contemporary environmental governance increasingly depends on accessible, standardized, and interoperable datasets capable of supporting cross-sectoral analysis and evidence-based policymaking. European initiatives such as the EU Open Data Portal, INSPIRE Directive[20], Danube Regional Data Space Infrastructures (DRDSI) [21], and UN-GGIM Integrated Geospatial Information Framework (IGIF)[22] establish institutional and technical foundations for secure and transparent environmental data governance.

In the context of the Dniester Basin, open-data ecosystems can facilitate cross-border information sharing, improve transparency, strengthen scientific cooperation, and support integrated environmental monitoring. At the same time, interoperability standards are essential for enabling the integration of heterogeneous datasets originating from different jurisdictions, monitoring systems, and institutional actors.

Based on these theoretical foundations, this study conceptualizes transboundary cyber-resilient water governance as a three-layer integrated framework , as shown in Figure 1.



Fig. 2. Governance layers of transboundary cyber-resilient water management
Source: Created by authors

1) The Data Layer - including IoT infrastructures, remote sensing systems, hydrological monitoring stations, and geospatial data ecosystems;
2) The Intelligence Layer - incorporating GeoAI analytics, machine-learning models, predictive simulations, and digital twin architectures;
3) The Operational Governance Layer - integrating multi-level coordination mechanisms, cybersecurity protocols, institutional interoperability, and transboundary policy frameworks.

This conceptual architecture forms the analytical basis for the proposed "EU Green Dniester–Black Sea Corridor" framework, which seeks to integrate digital monitoring, AI-enabled environmental intelligence, cyber-resilient infrastructure, and collaborative governance mechanisms into a coherent transboundary management model aligned with European climate and digital-transition strategies.

3. Current challenges of transboundary governance in the Lower Dniester Basin

The governance of the Lower Dniester Basin and the Dniester Liman is characterized by a high degree of institutional, technological, and environmental complexity. As a transboundary socio-ecological system shared by the Republic of Moldova and Ukraine, the basin operates within a fragmented governance environment shaped by asymmetries in administrative capacities, regulatory frameworks, digital infrastructures, and environmental management practices. Under conditions of accelerating climate change, growing anthropogenic pressure, and increasing dependence on digital monitoring systems, these structural limitations significantly constrain the ability of both states to establish an integrated, adaptive, and cyber-resilient governance model. From an institutional perspective, one of the principal challenges lies in the fragmentation of governance responsibilities across multiple administrative and sectoral levels. Water management functions are distributed among ministries, environmental agencies, hydrometeorological institutions, municipalities, infrastructure operators, and research organizations, often with limited interoperability between data systems and decision-making processes. This fragmentation reduces coordination efficiency, complicates emergency response mechanisms, and weakens the strategic integration of hydrological, environmental, and infrastructural planning.

Although bilateral cooperation mechanisms formally exist through the Moldovan-Ukrainian Dniester Commission, operational coordination remains constrained by uneven institutional capacities and inconsistent implementation practices. Existing cooperation frameworks primarily focus on environmental protection and hydrological regulation, while comparatively limited attention has been devoted to digital governance interoperability, cyber-resilience coordination, and integrated data governance architectures. Consequently, the institutional system remains largely reactive rather than

predictive and adaptive. A second critical challenge concerns the fragmentation and asymmetry of environmental and hydrological data infrastructures. Monitoring systems within the basin continue to operate through partially disconnected institutional platforms using heterogeneous standards for data collection, storage, and exchange. In many cases, environmental datasets remain geographically incomplete, temporally inconsistent, or institutionally inaccessible to local authorities and external stakeholders. This lack of interoperability significantly limits the capacity for real-time situational awareness and evidence-based decision-making. The absence of an integrated transboundary data ecosystem has direct implications for climate adaptation and risk management. Hydrological forecasting, flood prediction, drought assessment, and ecosystem monitoring require continuous and synchronized flows of high-quality environmental data across national borders. However, fragmented information architectures and institutional barriers prevent the establishment of unified predictive systems capable of supporting coordinated responses to extreme hydrological events.

Technological limitations further exacerbate governance vulnerabilities. Existing monitoring infrastructures in parts of the Dniester basin and Dniester Estuary areas continue to rely on outdated communication protocols, isolated sensor systems, and limited automation capacities. Rural and peripheral areas [23] frequently experience insufficient digital connectivity, reducing the reliability of environmental monitoring and restricting the deployment of advanced cyber-physical systems [24]. As a result, the region remains at an early stage of digital maturity in comparison with emerging European models of smart environmental governance. These technological gaps directly affect the implementation potential of advanced analytical tools such as GeoAI and digital twins. The operational effectiveness of AI-driven predictive systems depends on the availability of standardized, continuous, and interoperable datasets. Without integrated digital infrastructures, the capacity to develop dynamic simulations, scenario-based climate modeling, and adaptive decision-support systems remains significantly constrained.

An equally important dimension of the governance challenge concerns the increasing exposure of critical water infrastructures to cyber threats. The digitalization of environmental monitoring and water-management systems introduces new cyber-physical vulnerabilities affecting sensor networks, communication channels, cloud-based platforms, and operational control systems. In transboundary contexts, cyber risks acquire additional strategic significance due to the dependence of multiple jurisdictions on shared information infrastructures and synchronized environmental data flows. Cybersecurity weaknesses within water governance systems may result in data manipulation, unauthorized access, operational disruptions, or the degradation of trust between institutional actors. Compromised hydrological data or interruptions in communication infrastructures could undermine flood-warning systems, distort environmental assessments, and weaken the reliability of joint decision-making processes. Despite these risks, cybersecurity governance remains insufficiently institutionalized within existing transboundary cooperation frameworks.

Current governance arrangements lack dedicated mechanisms for cyber incident coordination, shared cybersecurity protocols, or integrated strategies for protecting

environmental digital infrastructures. This institutional gap reflects a broader disconnect between environmental governance and cybersecurity governance, despite the increasing convergence of ecological systems and digital infrastructures within contemporary smart-territory models.

Governance challenges in the Dniester River Basin and Dniester Estuary have a strong socio-political dimension with manifest asymmetrically across the interconnected socio-ecological system. Enhancing interoperability at transboundary, interregional, and transnational levels is addressed through the integration of Digital Twins of National Adaptation Hubs, cross-border SOCs, and Living Labs, forming the basis for cyber-resilient water governance (Figure 2).

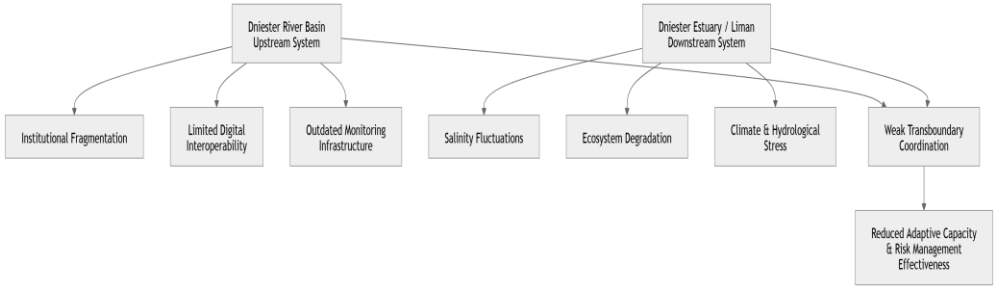


Figure 3. Interoperability-driven cross-river partnership[25] smart water governance
Source: Created by authors

Local municipalities and communities often remain weakly integrated into transboundary decision-making processes, limiting participatory governance capacities and reducing public trust in institutional coordination mechanisms. In many cases, local authorities face insufficient technical expertise, limited financial resources, and restricted access to digital monitoring tools necessary for implementing adaptive environmental policies. Furthermore, differences in administrative cultures, policy priorities, and regulatory practices between Moldova and Ukraine complicate the harmonization of environmental standards and governance procedures. These asymmetries generate institutional friction within transboundary cooperation processes and slow the implementation of interoperable digital governance architectures. The resulting governance environment is characterized by partial coordination rather than fully integrated basin-scale management.

Environmental pressures intensify these institutional and technological vulnerabilities. Climate-induced hydrological instability, increasing salinity fluctuations in the Dniester Estuary, biodiversity degradation, agricultural pollution, and growing pressure on water quality collectively increase the strategic importance of adaptive environmental governance. The ecological interconnectedness of the basin implies that localized environmental urban – rural linkages [26] may generate cascading transboundary effects affecting ecosystems, infrastructure, and socio-economic systems across the broader region. Under these conditions, traditional sectoral approaches to water governance become increasingly insufficient. Effective management of the Lower Dniester Basin requires the transition toward integrated cyber-physical governance systems capable of

combining environmental monitoring, predictive analytics, institutional coordination, and cybersecurity within a unified operational framework.

The governance experience of EUSDR Priority Areas related to water quality, inland navigation, biodiversity, and research coordination demonstrates the importance of combining environmental management with digital interoperability and institutional networking. Similarly, initiatives such as the Danube Civil Society Forum [27] highlight the growing role of participatory governance and stakeholder integration in transboundary environmental management. The inclusion of scientific institutions, local communities, civil society organizations, and regional authorities within collaborative governance platforms contributes to greater transparency, institutional trust, and long-term governance resilience. Within this context, the development of a transboundary cyber-resilient governance architecture for the cross - river cooperation becomes both a technological and institutional necessity. Such an approach requires the establishment of interoperable digital infrastructures, shared cybersecurity standards, integrated environmental intelligence systems, and multi-level coordination mechanisms capable of supporting adaptive and evidence-based governance.

The analysis presented in this section demonstrates that the principal governance challenges of the Lower Dniester Basin and Dniester Estuary at the European level, are not solely environmental or technological in nature. Rather, they emerge from the interaction between fragmented institutions, insufficient digital interoperability, cyber-physical vulnerabilities, and limited coordination capacities within a highly interconnected transboundary ecosystem. Addressing these challenges therefore requires a systemic governance transformation integrating digitalization, cyber-resilience, GeoAI analytics, and collaborative transboundary governance into a coherent strategic framework aligned with European climate and digital-transition policies.

4. Pilot projects and digital tools: Toward a conceptual implementation architecture for cyber-resilient transboundary water governance

Despite the growing strategic importance of digital transformation in environmental governance, the Lower Dniester Basin and the Dniester Liman currently lack a fully integrated cyber-physical infrastructure capable of supporting real-time, adaptive, and transboundary water management. Existing monitoring initiatives remain fragmented across institutional, technological, and territorial dimensions, consisting primarily of isolated hydrological observation stations, local environmental monitoring programs, research-driven pilot initiatives, and partially connected data-sharing mechanisms. While these initiatives provide valuable operational and scientific foundations, they do not yet constitute a coherent digital governance ecosystem capable of supporting integrated decision-making at basin scale.

From a governance perspective, the current stage of digitalization may be characterized as a transitional phase between conventional environmental monitoring and the emergence of intelligent, data-driven governance architectures. Existing infrastructures remain predominantly descriptive rather than predictive, reactive rather than adaptive, and institutionally segmented rather than interoperable. Consequently, the region faces

significant limitations in the implementation of advanced capabilities such as dynamic flood forecasting, climate-risk simulations, AI-assisted environmental management, and cyber-resilient operational coordination. In this context, pilot projects should not be understood merely as isolated technological experiments, but rather as strategic components of a broader conceptual implementation architecture designed to support the progressive transition toward integrated digital governance. Such pilot initiatives can function as experimental governance environments in which technological interoperability, institutional coordination, cybersecurity protocols, and participatory decision-making mechanisms are simultaneously tested under real operational conditions.

The transition toward a cyber-resilient smart water management ecosystem requires the establishment of an integrated architecture capable of connecting distributed monitoring systems, geospatial intelligence platforms, predictive analytics, and governance coordination mechanisms into a unified operational framework. Conceptually, this architecture may be structured around four interdependent dimensions: (i) environmental sensing infrastructure, (ii) digital intelligence and simulation systems, (iii) smart governance [28] and stakeholder coordination mechanisms, and (iv) cyber-resilience and infrastructure protection frameworks.

The first dimension consists of distributed environmental sensing infrastructures integrating hydrological stations, water-quality monitoring systems, meteorological sensors, biodiversity observation platforms, remote sensing technologies, and IoT-enabled environmental devices deployed across the Lower Dniester Basin and the Dniester Estuary. This infrastructure constitutes the foundational data-acquisition layer of the governance system. The objective of this layer is not solely the collection of environmental observations, but the establishment of continuous and interoperable real-time data streams capable of supporting predictive environmental intelligence.

Within this framework, the deployment of interoperable sensor networks becomes essential for overcoming existing fragmentation of monitoring infrastructures between Moldova and Ukraine. Standardization of data formats, communication protocols, and metadata architectures is necessary to ensure compatibility between national monitoring systems and broader European environmental data ecosystems. Integration with open-data infrastructures and geospatial interoperability standards further strengthens transparency and institutional coordination capacities.

The second dimension of the architecture involves the development of intelligent analytical infrastructures based on GeoAI and digital twin technologies in urban-rural studied areas [29] of the basin. In this context, GeoAI functions as the core analytical engine enabling the processing, interpretation, and prediction of complex environmental dynamics through machine learning, geospatial analytics, and spatial-temporal modeling techniques. The integration of GeoAI enables several critical governance functions:

- predictive flood and drought modeling;
- detection of hydrological anomalies;
- simulation of ecosystem degradation scenarios;
- salinity fluctuation forecasting in the Dniester Liman;

- identification of vulnerable environmental and infrastructural zones;
- optimization of resource allocation and emergency response planning.

Building upon these analytical capacities, the digital twin functions as the central integrative component of the governance architecture. The proposed GeoAI-enabled Digital Twin represents a dynamic cyber-physical model continuously updated through real-time environmental data streams. Unlike static monitoring platforms, the digital twin enables the simulation of interconnected hydrological, ecological, infrastructural, climatic, and socio-economic processes within a unified modeling environment.

The governance significance of the digital twin lies in its ability to support scenario-based and anticipatory governance. Through integrated simulations, decision-makers can evaluate the consequences of alternative policy interventions, climate adaptation strategies, infrastructure investments, and emergency-response measures before implementation. This capability transforms environmental management from a reactive administrative process into a predictive and adaptive strategic system. Importantly, the digital twin also functions as a transboundary coordination platform by providing shared situational awareness among Moldovan, Ukrainian, and European stakeholders. Through unified visualization interfaces and interoperable analytical dashboards, institutional actors can access synchronized environmental intelligence and collaboratively evaluate risk scenarios and governance alternatives.

The third dimension of the conceptual implementation architecture concerns governance coordination and stakeholder integration. Effective cyber-resilient water mangement cannot be achieved solely through technological modernization; it also requires institutional interoperability and participatory governance structures capable of integrating actors operating across multiple territorial and administrative scales. Within this framework, the proposed architecture incorporates multi-level governance mechanisms linking:

- local municipalities and water operators;
- regional environmental authorities;
- national hydrological and cybersecurity agencies;
- academic and research institutions;
- civil society organizations;
- European governance and funding mechanisms.

Such coordination structures are necessary for ensuring policy harmonization, operational interoperability, and institutional trust within transboundary decision-making processes. In particular, the integration of local communities into digital governance systems strengthens administration legitimacy and improves the responsiveness of adaptation strategies to territorial needs and environmental conditions. A central component of this administration layer is the proposed establishment of a Moldova–Ukraine Cyber-Resilient Water Security Hub functioning as a transboundary operational coordination center. The hub would support:

- real-time environmental data coordination;
- cyber incident monitoring and response;

- verification of sensor-data integrity;
- interoperability management between digital infrastructures;
- emergency coordination during hydrological or cyber-related crises;
- strategic cooperation with European environmental and cybersecurity frameworks.

The creation of such a hub reflects the increasing convergence between environmental mangement and critical infrastructure protection within contemporary smart-territory models.

The fourth dimension of the architecture concerns cyber-resilience and infrastructure security. As environmental mangement becomes increasingly dependent on interconnected digital infrastructures, cybersecurity emerges as a foundational condition for administration continuity and institutional trust. The proposed architecture therefore incorporates cyber-resilience principles at every operational layer, including:

- encryption of transboundary data flows;
- distributed data redundancy;
- secure cloud and edge-computing infrastructures;
- authentication and access-control mechanisms;
- AI-assisted anomaly detection;
- cyber incident response protocols;
- resilience-oriented infrastructure design.

This integrated approach shifts cybersecurity from a supplementary technical function toward a core governance principle embedded within environmental management processes. Although the Dniester Basin is not formally part of the Danube administration system, it remains functionally connected to wider Black Sea and Eastern European environmental mangement networks. Consequently, the adaptation of macro-regional digital governance models provides important institutional and methodological guidance for the development of interoperable transboundary water-management systems.

Several European pilot initiatives provide relevant conceptual precedents for the proposed architecture. Projects such as IDEATION[30], EcoTwin[31], European DTO[32], Gironde[33], and MARCLAIMED[34] demonstrate the operational potential of integrating digital twins, AI-based environmental analytics, open-data infrastructures, and participatory governance mechanisms within complex environmental systems. These initiatives illustrate how cyber-physical governance platforms can support climate adaptation, ecosystem monitoring, and transboundary coordination through integrated digital ecosystems. After the general justification of pilot initiatives, we propose in figure 3, a conceptual implementation architecture.

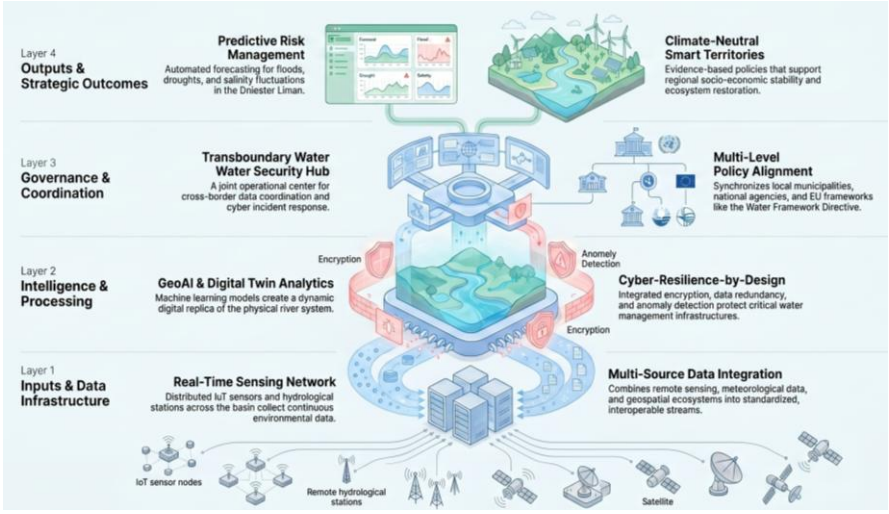


Fig. 4. The GeoAI Architecture for Cyber-Resilient Water Governance
Source: Created by authors

In the context of the Lower Dniester and Dniester Estuary Basins, the proposed conceptual implementation architecture therefore represents more than a technological modernization strategy. It constitutes a systemic governance transformation framework aimed at integrating environmental intelligence, digital infrastructures, cyber-resilience, and institutional interoperability into a coherent model of adaptive transboundary governance.

The architecture ultimately supports the emergence of a cyber-resilient digital ecosystem capable of:

- enabling real-time environmental intelligence;
- strengthening climate adaptation capacities;
- improving institutional coordination;
- supporting evidence-based policymaking;
- protecting critical environmental infrastructures;
- and facilitating long-term sustainable development in the Dniester Basin and Black Sea macro-regional context.

Through this approach, pilot projects evolve from isolated technological interventions into foundational components of a scalable and interoperable governance ecosystem aligned with European digital-transition and climate-resilience strategies.

5. Policy and implementation recommendations

The transition toward cyber-resilient smart water management in the Lower Dniester Basin requires a coordinated set of institutional, technological, and policy interventions implemented across multiple management levels.

Given the transboundary nature of the basin and the existing asymmetries between Moldova and Ukraine, these measures must prioritize interoperability, institutional coordination, and cybersecurity integration.

First, the establishment of a transboundary digital governance mechanism between Moldova and Ukraine is essential. This mechanism should ensure coordinated management of environmental data, harmonized monitoring standards, and unified cybersecurity protocols. It should also support joint decision-making processes for water resource management and climate adaptation.

Second, the deployment of an integrated IoT-based environmental monitoring infrastructure is required to enable real-time, standardized, and interoperable data collection across the basin and the Dniester Liman. Such infrastructure should ensure continuous environmental sensing, covering hydrological, meteorological, ecological, and water-quality parameters.

Third, the development of a GeoAI-enabled Digital Twin system should be prioritized to support predictive analytics for flood risks, drought dynamics, salinity fluctuations, and ecosystem changes. This system would provide a decision-support environment for scenario-based planning and evidence-based policy formulation.

Fourth, the creation of a Cyber-Resilient Water Security Hub is recommended as a transboundary coordination structure responsible for cybersecurity monitoring, incident response, verification of data integrity, and protection of critical environmental infrastructures. The hub should function as an operational interface between national institutions and European cybersecurity and environmental management frameworks.

Fifth, the implementation of pilot Living Lab environments across selected areas of the basin is necessary to test integrated digital governance solutions under real operational conditions. These environments should support experimentation with IoT systems, AI models, administration protocols, and cybersecurity mechanisms, ensuring scalability and transferability of solutions.

Finally, all interventions should be aligned with relevant European and international frameworks, including the Water Framework Directive (WFD), the Marine Strategy Framework Directive (MSFD), the EU Strategy for the Danube Region (EUSDR), Horizon Europe Missions, and the UN-GGIM Integrated Geospatial Information Framework (IGIF). This alignment ensures institutional compatibility with EU climate, digital, and environmental mangement standards.

6. Conclusions

This study demonstrates that transboundary water management in the Lower Dniester Basin and the Dniester Estuary is currently constrained by institutional fragmentation, limited digital interoperability, and insufficient cyber-resilience of critical environmental infrastructures. These constraints reduce the effectiveness of real-time monitoring, predictive analytics, and coordinated decision-making between Moldova and Ukraine.

The research confirms that addressing these challenges requires a systemic transition from fragmented monitoring systems toward an integrated cyber-physical administation architecture. Such an architecture is based on the convergence of IoT-enabled environmental sensing, GeoAI-driven analytics, digital twin modeling, and multi-level transboundary administration mechanisms. The proposed conceptual framework - the Cyber-Resilient Smart Water Management model for the Dniester Basin and Dniester Estuary - illustrates how environmental intelligence, digital infrastructures, institutional coordination, and cybersecurity can be integrated into a unified adaptive governance system aligned with EU climate and digital transition strategies.

The study contributes to the development of a scalable governance paradigm for transboundary river basins, in which environmental management, digital transformation, and cyber-resilience are treated as interdependent dimensions of a single socio-technical system. It further advances the conceptual integration of GeoAI and digital twin technologies into climate-adaptive water mangement and highlights the importance of embedding cybersecurity as a foundational administration principle rather than a peripheral technical function.

Implementation of the proposed recommendations requires a phased, coordinated, and institutionally supported approach. The transition toward cyber-resilient smart water management should be understood not as a discrete technological upgrade, but as a systemic transformation involving institutional reform, digital infrastructure development, and the integration of advanced analytical and cybersecurity capabilities within transboundary environmental administration systems.

References

[1] EU Commission, The Directive on the Resilience of Critical Entities entered into force on 16 January 2023 https://eur-lex.europa.eu/eli/dir/2022/2557/oj ;

[2] Namysłowska M., Olbryk A., “Smart governance in Poland: The case study of the city of Łódź”, Smart Cities and Regional Development (SCRD) Journal, Vol. 9, No. 3, 2025. Available at: https://www.scrd.eu/index.php/scrd/issue/view/46 ;

[3] EU Commission, European Climate Adaptation Platform Climate-ADAPT, « Multi-level and cross-sectoral governance»: https://climate-adapt.eea.europa.eu/en/metadata/adaptation-options/multi-level-and-cross-sectoral-governance-schemes-for-climate-change-adaptation ;

[4] OSCE, Leonid Kalashnyk, Ursula Froese, «Dniester River Basin» : https://www.osce.org/magazine/211691 ;

[5] Respublic of Moldova, Lower Dniester National Park: https://lower-dniester.org/ ;

[6] UNECE, Global Environment Facility’s project “Enabling transboundary co-operation and integrated water resources management in the Dniester River Basin”, Dniester Estuary (Liman):https://dniester-commission.org/en/dniester-river-basin/region/;

[7] EU Commission,Water Framework Directive (WFD): https://environment.ec.europa.eu/topics/water/water-framework-directive_en ;

[8] EU Commission, «EU Marine Strategy Framework Directive», 2008: https://eur-lex.europa.eu/eli/dir/2008/56/oj/eng ;

[9] Council of Europe, The European Green Deal is the EU's growth strategy https://www.consilium.europa.eu/en/policies/european-green-deal/ ;

[10] EU Commission, EU Strategy for the Danube Region https://projects.research-and-innovation.ec.europa.eu/en/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/restore-our-ocean-and-waters/danube-region-programme-2021-2027-0

[11] EU Commission, EU Missions in Horizon Europe: https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe_en ;
[12] EU Commission, "Europe's Internet of Things policy": https://eur-lex.europa.eu/EN/legal-content/summary/internet-of-things.html ;
[13] EU Commission, Interoperable Europe, Lorena HERNANDEZ , ELISE webinar: GeoAI , Presentation: Geospatial Data and Artificial Intelligence - a deep dive into GeoAI: https://interoperable-europe.ec.europa.eu/collection/elise-european-location-interoperability-solutions-e-government/document/presentation-geospatial-data-and-artificial-intelligence-deep-dive-geoai ;
[14] ITU, Recommendation ITU-T Y.4237 specifies the requirements and capability framework of the digital twin for intelligent water conservancy system (DT-IWCS): https://www.itu.int/itu-t/recommendations/rec.aspx?rec=16204&lang=en;
[15] EU Commission, European External Actions Services (EEAS), «New EU strategy for secure, prosperous and resilient Black Sea region», 2025: https://www.eeas.europa.eu/delegations/ukraine/new-eu-strategy-secure-prosperous-and-resilient-black-sea-region_en;
[16] EU, Danube Region Strategy addresses a wide range of issues; these are divided among 4 pillars and 12 Priority Areas, 2021: https://danube-region.eu/about-eusdr/eusdr-governance-priority-areas/ ;
[17] EU, Documentation of the European Data Portal (EDP), «The 2024 Geospatial Trends Report: Geospatial digital twins and their relevance»: https://data.europa.eu/en/news-events/news/2024-geospatial-trends-report-geospatial-digital-twins-and-their-relevance ;
[18] EU Commission, Commission launches call for evidence on digital action plan for water sector, 2026: https://environment.ec.europa.eu/news/commission-seeks-input-digital-action-plan-water-sector-2026-05-27_en
[19] EU Commission, «National Adaptation Hubs: Strengthening National Governance for the EU Mission on Adaptation to Climate Change»: https://mission-adaptation-portal.ec.europa.eu/about/national-adaptation-hubs_en
[20] EU, Commission, Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE) : https://knowledge-base.inspire.ec.europa.eu/legislation/inspire-directive_en ;
[21] Joint Research Center EU Commission, «Digital Regional Data Space Infrastructures» (DRDSI), 2015: https://data.europa.eu/en/publications/use-cases/danube-reference-data-and-services-infrastructure-drdsi
[22] UN-GGIM Integrated Geospatial Information Framework (IGIF) : https://ggim.un.org/UN-IGIF/ ;
[23] Babin A., Tutunaru S., Covalenco I., "Cybersecurity and smart innovation for rural resilience: Moldova's strategic transition to green and digital villages", TRUST Proceedings, 2026. Available at: https://scrd.eu/index.php/trust/article/download/745/777/1768 ;
[24] EU Commission, "Cyber-Physical European Roadmap & Strategy", 2015: https://digital-strategy.ec.europa.eu/en/news/cyber-physical-european-roadmap-strategy ;
[25] https://crossriverpartnership.org/
[26] Rosca M., Ciobanu R., "Smart Cities and the Rural-Urban Divide in Moldova: Balancing Innovation and Tradition", Smart Cities and Regional Development (SCRD) Journal, Vol. 9, No. 3, 2025. Available at: https://www.scrd.eu/index.php/scrd/issue/view/46 ;
[27] EU, Danube Civil Society Forum : https://danubestrategy.eu/about ;
[28] Vrabie C., "Editorial: From Smart Systems to Smart Governance", Smart Cities and Regional Development (SCRD) Journal, Vol. 10, No. 2, 2026. DOI: https://doi.org/10.25019/wya1f992 ;
[29] Frida ZISKO , Besjana MEMA , "Digital twins and MIS integration for urban resilience: A strategic approach to smart city evolution " Smart Cities and Regional Development (SCRD) Journal. 10, 2 (Apr. 2026), 35–50. DOI: https://doi.org/10.25019/6df15r93 ;
[30] EU Commission, Horizon Europe, "IDEATION - InlanD watErs in the digitAl TwIn OceaN" 2024-2026: https://cordis.europa.eu/project/id/101157371 ;
[31] EU Commission, Horizon Europe project, "ECOTWIN - Emulating complex causal socio-ecological models in digital twins of ocean", 2024-2027 : https://cordis.europa.eu/project/id/101157369 ;
[32] EU Commission, EDITO: the core infrastructure of the European Digital Twin Ocean, building on existing assets: https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/restore-our-ocean-and-waters/european-digital-twin-ocean_en ;

[33] EU, France, GIRondeOpenSource is a project conducted by Egis: https://connectwin.egis-group.com/en/fiche-reference/the-gironde-europes-largest-estuary-gets-a-digital-twin/ ;
[34] EU Commission, Horizon Research and Innovation Programme under Grant Agreement N.101136799: https://cordis.europa.eu/project/id/101136799/results