IMPLEMENTATION OF THE STRATEGIC ACTION PROGRAMME (SAP) OF THE DINARIC KARST AQUIFER SYSTEM: IMPROVING GROUNDWATER GOVERNANCE AND SUSTAINABILITY OF RELATED ECOSYSTEMS

OUTPUT 2.1.

NATIONAL GROUNDWATER GOVERNANCE DIAGNOSTIC ANALYSIS CROATIA

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Content

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1 Introduction

The DIKTAS II Project Document mandates the conduct of a Groundwater Governance Diagnostic Analysis (GGDA) in all participating countries. This includes a comprehensive stocktaking of the current governance landscape - covering institutional actors, legal frameworks, policies and plans, alignment with the EU Water Framework Directive (WFD) and Groundwater Directive (GWD), available knowledge, enforcement capacities, and an assessment of existing gaps and opportunities (requirements from: Component 2, Outcome 2, Output 2.1).

To achieve the objectives of Component 2: Institutional Strengthening for Improved Groundwater Governance, the GGDA should be implemented in two phases: first, as national-level GGDAs in each project country, and second, as a regional/transboundary GGDA. The items and guiding questions addressed in the national GGDAs serve to evaluate the current state of groundwater governance principles in each country. The outputs of these national analyses - developed using harmonized criteria - will inform the identification of key pathways for establishing effective and responsive groundwater governance across the six transboundary areas (TBAs) defined in the Transboundary Diagnostic Analysis (TDA) of the DIKTAS I project. Finally, a common set of indicators applicable to all TBAs need to be defined, which will be used to assess the implementation of enabling frameworks and guiding principles for sustainable groundwater management in the future.

The Croatian Groundwater Governance Diagnostic Analysis (CGGDA) was conducted in accordance with the guidelines outlined in the final output of the GEF/FAO Groundwater Governance Project (GGP), titled “Global Framework for Action to Achieve the Vision on Groundwater Governance.” This document presents the results of a global initiative aimed at strengthening groundwater governance at transboundary, national, and local levels.

Following the GGP recommendations, the CGGDA assessed the status of groundwater governance in Croatia, with particular emphasis on the Dinaric karst regions, to identify the most relevant governance improvements and explore how they can be tailored to local conditions and challenges. The analysis focused on identifying strengths, gaps, shortcomings, and opportunities for enhancement.

The following section provides a brief overview of the contents of the main chapters of this document.

Chapter 2 – Actors in Groundwater Governance

This chapter identifies the key institutional, regional, and local actors involved in groundwater governance in Croatia, including ministries, agencies, public health institutes, utility companies, and NGOs. It describes the vertical and horizontal coordination mechanisms, highlighting formal structures and informal project-based cooperation. The chapter assesses institutional capacities, financial resources, and technical expertise, with emphasis on disparities between national and local levels. It also evaluates the level of awareness among stakeholders, noting strong institutional understanding but limited public engagement.

Chapter 3 – Legal Framework

This chapter outlines the legal instruments governing groundwater in Croatia, primarily the Water Act and its associated regulations, which are harmonized with EU directives (WFD and GWD). It details the provisions for groundwater monitoring, abstraction permits, sanitary protection zones, and pollution control, especially in karst areas. The chapter explains the methodology for setting threshold values and environmental quality standards, and discusses enforcement mechanisms, including inspections, penalties, and institutional responsibilities. It also highlights legal gaps, particularly in regulating artificial recharge, wastewater discharge, and protection of groundwater-dependent ecosystems.

Chapter 4 – Policies, Plans and Principles

This chapter reviews Croatia's strategic and sectoral policy documents relevant to groundwater governance, including the Water Management Strategy, River Basin Management Plan, and sectoral strategies, particularly of agriculture, tourism, energy, and spatial development. It analyses the degree of integration and coherence among these policies, noting alignment with EU objectives but limited operational coordination. The chapter emphasizes the importance of tailored approaches in karst regions and the role of financial instruments such as eco-schemes in promoting sustainable practices. It also discusses monitoring systems, pollution control measures, and the need for improved cross-sectoral planning.

Chapter 5 – Adherence to the WFD and GWD

This chapter assesses Croatia's compliance with the EU Water Framework Directive and Groundwater Directive through national legislation and implementation practices. It describes the transposition of directive provisions into the Water Act and related regulations, including the establishment of groundwater bodies, monitoring obligations, and threshold values. The chapter explains the methodologies used for chemical status assessment, particularly in karst aquifers, and evaluates the designation of drinking water protection areas. It identifies conceptual ambiguities in aligning sanitary protection zones with EU definitions of protected groundwater bodies.

Chapter 6 – Knowledge, Information and Awareness

This chapter presents the status of groundwater-related data collection, monitoring programs, and information systems in Croatia. It details the types of data available - water quality, abstraction volumes, ecological flows, and biodiversity indicators - and the institutions responsible for their collection and dissemination. The chapter evaluates public access to data, noting limitations in interoperability and raw data availability. It also discusses awareness levels among stakeholders and the public, emphasizing the need for improved communication, education, and integration of groundwater-dependent ecosystem data.

Chapter 7 – Socio-economic Setting and Challenges

This chapter analyses the socio-economic context affecting groundwater governance in Croatia, with a focus on karst regions. It identifies key challenges such as illegal waste disposal, infrastructure

deficits, seasonal tourism pressures, and weak inter-sectoral coordination. The chapter highlights the economic importance of groundwater for drinking water supply, energy production, agriculture, and tourism, and outlines risks to groundwater-dependent ecosystems. It proposes opportunities for improvement through enhanced monitoring, stricter regulation, integrated data systems, and increased public participation.

Chapter 8 – SWOT Analysis

This chapter presents a structured assessment of Croatia's groundwater governance through a SWOT framework, identifying key strengths, weaknesses, opportunities, and threats. It highlights institutional robustness, legal alignment with EU directives, and technical expertise as strengths, while pointing to fragmented coordination, limited public awareness, and regulatory gaps in karst areas as weaknesses. Opportunities include improved monitoring, digitalization, environmental incentives, and transboundary cooperation, whereas threats stem from illegal waste disposal, tourism pressures, and climate-related risks.

Chapter 9 – Gaps and Opportunities

This chapter synthesizes the diagnostic findings to outline critical governance gaps and actionable opportunities, with a focus on the Dinaric karst region. It emphasizes deficiencies in cross-sectoral integration, risk assessment, and data interoperability, while proposing targeted improvements such as site-specific legal instruments, enhanced stakeholder engagement, and strategic investments in monitoring and infrastructure. The analysis serves as a foundation for future reforms and regional cooperation under the DIKTAS framework.

2 Actors in groundwater governance

The main actors in groundwater governance and management in Croatia operate at multiple levels. At the national level, the Ministry of Environmental Protection and Green Transition (Directorate for Water Management and Sea Protection) and Croatian Waters are responsible for strategic planning, supervision, and implementation of water resource management policies. The Croatian Institute of Public Health – Andrija Štampar Institute and the network of county public health institutes regularly conduct analyses of drinking water quality. At the regional and local levels, county public institutions and municipal utility companies (e.g., Ličke vode Ltd., Dubrovnik Water Utility, Split Water Utility, Rijeka Water Utility) manage water supply and wastewater systems. Non-governmental organizations such as Green Action (Zelena akcija), Croatian Water Pollution Control Society, WWF Adria, and ZMAG, together with civic initiatives like Rotary Croatia, also play important roles in raising awareness and implementing water protection projects.

In Croatia, the institutional framework for groundwater management is established through the Water Act (Official Gazette, No. 66/2019, 84/2021, 47/2023) and the River Basin Management Plan of the Republic of Croatia until 2027 (Official Gazette No. 84/2023), ensuring vertical coordination between national, regional, and local levels. At the national level, the Ministry of Environmental Protection and

Green Transition defines strategies and legislation, while Croatian Waters oversee implementation and supervision. At the local level, municipalities and public utility companies manage operational tasks such as water supply, wastewater, and source protection. Horizontal coordination exists with sectors such as agriculture, energy, tourism, health, and nature protection, but this cooperation is often project-based (e.g., EU LIFE, INTERREG, DIKTAS) rather than systematic. Although the institutional set-up formally integrates vertical and horizontal functions, further strengthening of inter-sectoral coordination and information exchange remains necessary for effective groundwater governance

Institutions responsible for groundwater management in Croatia demonstrate varying levels of capacity, expertise, and financial support. Croatian Waters and new Water Institute Josip Juraj Strossmayer possess substantial technical expertise and long-standing experience in planning, monitoring, and managing water resources, though modernization and digitalization efforts are constrained by limited budgets. The Croatian Institute of Public Health and its network of county institutes have well-developed laboratory systems for water quality control, yet continuous investment in equipment and staff training remains necessary, particularly in karst and rural regions. At the local level, public utility companies (e.g., Ličke vode Ltd., Zadar Water Utility, Šibenik Water and Sewerage Company) often face financial and technical constraints that hinder the maintenance of infrastructure in mountainous or depopulated areas. Overall, national institutions possess adequate strategic capacity, whereas local entities exhibit uneven operational capabilities depending on their financial and human resources

Cooperation among different actors in groundwater management in Croatia can be assessed as reasonable, though uneven across levels and sectors. At the national level, collaboration between the Ministry of Environmental Protection and Green Transition, Croatian Waters, and the Croatian Institute of Public Health occurs regularly through the implementation of the Water Act and the River Basin Management Plan. However, horizontal coordination between sectors, particularly tourism, agriculture, and energy, remains mostly project-based rather than systematically institutionalized. Cooperation between public authorities and non-governmental organizations exists through campaigns and environmental projects but lacks formal mechanisms for participation in policy-making. Overall, inter-agency cooperation is functional but would benefit from stronger cross-sectoral integration and more active involvement of local communities and civil society

Awareness of groundwater and groundwater governance among different groups of actors in Croatia can generally be described as moderate to good at the institutional and expert levels, but fragmented and insufficiently developed among the wider public.

At the national and institutional level, awareness is high; Croatian Waters, the Ministry of Environmental Protection and Green Transition, and the Croatian Institute of Public Health regularly emphasize the strategic importance of groundwater in official reports, monitoring programs, and campaigns such as World Water Day 2022 – “Making the Invisible Visible” (HZJZ, 2022). Public institutions are well informed about the vulnerability of groundwater systems, particularly in karst areas, but awareness often remains within administrative and professional circles, without being systematically translated into public education or participatory governance.

At the local level, awareness is more reactive and project based. Communities become aware of groundwater issues primarily when facing problems with supply or quality. Generally, both a high local sensitivity to water issues and the uneven institutional coverage across Croatia exist, and rural settlements still face challenges in access to clean water.

Among the general public, awareness is mostly linked to the concept of “drinking water” rather than to the specific role and vulnerability of groundwater. Media and environmental organizations highlight the importance of water conservation, but knowledge of groundwater systems, recharge zones, and pollution risks remains limited. Public discourse tends to focus on visible problems such as network losses and water scarcity during summer months rather than on long-term groundwater protection.

In the academic and expert community, awareness and research activity are strong – scientific studies address groundwater pollution, monitoring, and the impacts of climate change. However, there is a notable absence of research specifically focused on public awareness or attitudes toward groundwater. Neither the Croatian Bureau of Statistics nor national environmental agencies have published surveys or representative data assessing citizens’ knowledge or perceptions of groundwater governance.

Overall, Croatia demonstrates a solid institutional understanding of groundwater management but lacks broad social awareness and consistent communication between experts, policymakers, and the public. Awareness is highest among professional and scientific actors, moderate among local governments and NGOs, and weakest among citizens. Addressing this gap requires systematic education, participatory programs, and communication campaigns that connect the invisible dimension of groundwater with visible everyday concerns such as water quality, access, and resilience to climate change.

3 Legal framework

Groundwater in Croatia is regulated primarily by the Water Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023), which defines water as a public good and sets rules for its use, protection, and monitoring. Waters in surface and groundwater bodies cannot be the object of ownership rights and other real rights.

According to the Water Act, groundwater monitoring in Croatia is conducted to assess the status of water bodies, identify pollution trends, and evaluate the effectiveness of water protection measures. It includes both chemical indicators and quantitative data and is carried out by the national water management authority, Croatian Waters, and by new Water Institute Josip Juraj Strossmayer. Water for Human Consumption Act ("Official Gazette" No. 30/2023) governs the quality and safety of water intended for human consumption, including the responsibilities of competent authorities and water suppliers, conformity parameters, risk-based safety management, monitoring procedures, and enforcement measures, with the aim of protecting public health from adverse effects of water contamination. The Rulebook on conformity parameters, analytical methods, and monitoring of water intended for human consumption (Official Gazette No. 64/2023, 88/2023) is adopted pursuant to the Water for Human Consumption Act and serves as its implementing regulation, detailing technical standards and procedures for ensuring water quality and safety.

The Water Management Financing Act ("Official Gazette" No. 153/2009, 90/2011, 56/2013, 154/2014, 119/2015, 120/2016, 127/2017, 66/2019, 36/24) ensures funding through water charges, service fees, and public budgets. The Environmental Protection Act ("Official Gazette" No. 80/2013, 153/2013, 78/2015, 12/2018, 118/2018) integrates water protection into broader sustainability goals, including pollution control and public participation. The Nature Protection Act ("Official Gazette" No. 80/2013,

15/2018, 14/2019, 127/2019, 155/2023) safeguards groundwater-dependent ecosystems and biodiversity, prohibiting harmful activities in protected areas. Civil Protection Act ("Official Gazette" No. 82/2015, 118/2018, 31/2020, 20/2021, 114/2022) addresses flood risks and emergency responses related to water pollution. Waste Management Act ("Official Gazette" No. 84/2021), covers remediation and management of contaminated sites including soil and groundwater, emphasizing prevention of contamination and clean-up responsibilities. Forest Act ("Official Gazette" No. 68/18, 115/18, 98/19, 32/20, 145/20, 101/23, 36/24) defines water protection as one of the general beneficial functions of forests and stipulates that forest management and infrastructure must be organized and implemented with the aim of avoiding harmful effects on waters (watercourses, springs, reservoirs) and water quality and quantity.

Croatia's Water Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023) and subordinate legislation adopted pursuant to the Water Act, fully transposes the Water Framework Directive, WFD (Directive 2000/60/EC) and the Groundwater Directive, GWD (Directive 2006/118/EC, 2014/80/EU). It defines groundwater bodies, sets environmental objectives, and establishes criteria for assessing chemical and quantitative status, including monitoring obligations. The Act also incorporates Annexes II and V of the WFD and Annex I of the GWD, ensuring systematic monitoring and classification of groundwater status.

The Environmental Protection Act ("Official Gazette" No. 80/2013, 153/2013, 78/2015, 12/2018, 118/2018) complements this by transposing Directive 2004/35/EC on environmental liability and Directive 2003/4/EC on public access to environmental information, supporting transparency and accountability in groundwater protection. The Nature Protection Act ("Official Gazette" No. 80/2013, 15/2018, 14/2019, 127/2019, 155/2023) transposes Directive 92/43/EEC on the conservation of natural habitats and Directive 2009/147/EC on the protection of wild birds, thereby safeguarding groundwater-dependent ecosystems through ecological network planning and biodiversity conservation. The Regulation on Water Quality Standards ("Official Gazette" No. 96/2019, 20/2023, 50/2023), in the section concerning groundwater, defines the criteria for assessing the chemical status of groundwater bodies based on groundwater quality standards and threshold values of concentrations of pollutants. These legislative instruments are coordinated through Croatia's River Basin Management Plans and executed by Croatian Waters, ensuring compliance with EU obligations and the sustainable management of groundwater resources.

In Croatia, the legal basis for assessing and monitoring the chemical and quantitative status of groundwater in karst areas is established by the Water Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023) and the Regulation on Water Quality Standards ("Official Gazette" No. 96/2019, 20/2023, 50/2023), which transpose Articles 4 and 5 of the GWD and Annexes II and V of the WFD. These regulations define environmental objectives, chemical status criteria, and monitoring obligations for groundwater bodies. The national methodology, adopted in the River Basin Management Plans (RBMPs) until 2027 ("Official Gazette" No. 84/2023), includes the determination of background concentrations and threshold values for pollutants, tailored to the hydrogeological characteristics of karst systems. The tiered approach recommended by the BRIDGE project and CIS Guidance Document No. 18 is used to define threshold values for chemical status and risk assessment. For groundwater-dependent ecosystems, such as springs and speleological habitats, environmental quality standards (EQS) are applied to ensure ecological integrity. The methodology also includes classification tests for saline intrusion, surface water interaction, and terrestrial ecosystems, as outlined in CIS Guidance Document No. 18. In karst areas, threshold values are often set at the river basin level due to

hydrogeology and limited data availability. The precautionary principle is applied when determining threshold values, especially for drinking water protection zones and sensitive ecosystems.

Use of water (surface or groundwater) is regulated by Water Act through Concession and Permits (Ministry of Environmental Protection and Green Transition is responsible for Concessions and Croatian Waters for Permits) - and the procedure is defined in the Rulebook on the issuance of water acts ("Official Gazette" No. 9/2020, 39/2022). Beside water use, there are also Permits for water discharge (IPPC Permit - issued by Ministry of Environmental Protection and Green Transition and water discharge Permits issued by Croatian Waters).

Water Use Permits are issued by Croatian Waters for a period of 12 years for: public water supply, technological water and irrigation for quantities less than 10,000 m3 per year. Water Use Concessions are issued by the Ministry of Environmental Protection and Green Transition for the economic use of water: waterpower to produce electricity, technological water and irrigation for quantities greater than 10,000 m3 per year; the abstraction of mineral and geothermal waters and water for human consumption for placing on the market. Concessions are issued for a period of 30 or 40 years (production of electricity). The user of a Water Use Permit or Water Use Concession is obliged to keep records of the abstracted quantities of water (record book) and submit data to Croatian Waters and pay a fee accordingly.

Croatia's water legislation integrates the polluter pays and cost recovery principles in alignment with the EU Water Framework Directive (2000/60/EC). The Water Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023) establishes the legal framework for water management, including the obligation to recover costs related to water services and environmental protection. It mandates that water pricing policies reflect the economic value of water, encompassing resource, operational, infrastructure, and environmental costs. The Water Management Financing Act ("Official Gazette" No. 153/2009, 90/2011, 56/2013, 154/2014, 119/2015, 120/2016, 127/2017, 66/2019, 36/2024) further elaborates on these principles, stating that users and polluters must contribute to financing through water fees and service charges. Article 3.a of this Act explicitly defines water's economic value and outlines mechanisms for cost recovery through pricing policies. It also requires differentiation among user categories (industry, households, agriculture) and considers social, environmental, and economic impacts. The River Basin Management Plan, regulated under the Water Act, must include a report on the implementation of cost recovery and polluter pays principles. Additionally, based on the Water Services Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023, 110/2024), the Council for Water Services plays a regulatory role in ensuring these principles are applied, including the integration of environmental and resource costs into pricing structures. These provisions are supported by by-laws such as the Regulation on Water Service Pricing Methodology ("Official Gazette" No. 70/2023), which operationalizes cost recovery and ensures transparency and fairness in tariff structures. Overall, Croatia's legal framework ensures that water users and polluters bear the financial responsibility for water use and environmental impacts, promoting sustainable water management

Pursuant to the Water Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023), all public water supply sources - whether existing or planned, including springs, wells, lakes, and rivers - are required to establish sanitary protection zones (SPZs) to safeguard water quality and public health. The Rulebook on the Conditions for Establishing Sanitary Protection Zones of Water Sources ("Official Gazette" No. 66/2011, 47/2013) prescribes the procedural and technical requirements for the designation of SPZs, including the scope of protective measures, applicable restrictions within designated zones, relevant timeframes, and the decision-making process

The Rulebook on the Conditions for Establishing Sanitary Protection Zones of Water Sources classifies aquifers into two categories - karst and alluvial - and prescribes the number of protection zones, criteria for their delineation, and corresponding protective measures, including prohibitions and restrictions. For karst aquifers, four sanitary protection zones are defined: Zone IV (Restriction Zone), Zone III (Restriction and Control Zone), Zone II (Strict Restriction and Control Zone), and Zone I (Strict Protection Regime and Control Zone). Due to their high vulnerability, ponors are to be classified as Zone II areas and, where feasible and appropriate, must be physically fenced. The establishment of sanitary protection zones requires comprehensive hydrogeological investigations, which must include geological, hydrological and chemical analyses. For karst areas, hydrogeological studies assess the type of aquifer (e.g. fractured or karstic), its recharge mechanisms, flow velocity, natural purification capacity, identification of aquifer boundaries, water quality, and vulnerability to pollution. If areas of collection, retention and discharge of water to the water supply source are in mountainous regions outside the zones of sanitary protection, these areas may be designated as separate water supply reserves. In these areas, the passive protection measures applicable in zones IV, III and II of sanitary protection can be implemented.

The 2011 Rulebook on conditions for establishing the zones of sanitary protection of water sources prescribes that Croatian Waters, as the national water agency, is responsible for issuing technical guidelines for the delineation of sanitary protection zones. These guidelines are intended to support local and regional authorities, as well as hydrogeological experts, in making informed decisions regarding the establishment of protection zones. However, they were never adapted. Although the Rulebook on the Conditions for Establishing Sanitary Protection Zones of Water Sources from 2002 is no longer in force, national-level Guidelines adopted under its framework provided a detailed methodology for determining sanitary protection zones in karst terrains. These Guidelines included procedures such as the preparation of hydrogeological maps, geophysical investigations, determination of hydrodynamic parameters, groundwater level monitoring, water quality assessments, hydrogeochemical research, groundwater flow tracing, water balance analysis, and the establishment of a cadastre of potential pollution sources.

Protective measures in sanitary protection zones in Croatian karst areas are defined through a combination of passive and active measures, as outlined in the Rulebook on the Conditions for Establishing Sanitary Protection Zones of Water Sources (“Official Gazette” No. 66/2011, 47/2013). Passive measures include prohibitions on certain activities within designated zones, while active measures involve regular water quality monitoring, wastewater pre-treatment, infrastructure improvements, and clean production practices. In karst terrains, strict prohibitions apply in all zones, including bans on waste disposal, construction of hazardous facilities, and agricultural activities unless ecological practices are used. Active measures include mandatory hydrogeological investigations and monitoring of water quality. Exceptionally, certain developments (e.g. waste management centres) may be allowed in zone III if detailed studies prove no risk to groundwater and strict protective conditions are met.

The methodology for groundwater monitoring in karst areas, in accordance with the requirements of the Water Framework Directive and the Groundwater Directive, was defined in 2016 as part of the preparations for the development of the River Basin Management Plan for the period up to 2021. The monitoring strategy emphasizes precautionary principles and basin-level assessments. Chemical monitoring includes parameters such as nitrates, chlorides, ammonium, electrical conductivity, and phosphates, which are sensitive indicators of anthropogenic impact. The River Basin Management Plan (RBMP) until 2027 (“Official Gazette” No. 84/2023) incorporates methodologies for evaluating

chemical status and risk in karst groundwater bodies, including the protection of groundwater-dependent terrestrial and aquatic ecosystems (GWDTEs). Environmental Quality Standards (EQS) are applied to assess impacts on connected ecosystems and surface waters. Monitoring of the chemical and quantitative status of groundwater, in accordance with the Water Framework Directive (WFD) and the Groundwater Directive (GWD), as transposed into national legislation through the Regulation on Water Quality Standards Regulation on Water Quality Standards ("Official Gazette" No. 96/2019, 20/2023, 50/2023), is complemented by the monitoring of karst springs and wells used for public water supply, pursuant to the requirements for drinking water surveillance.

Due to limited monitoring data and high natural variability, background concentrations of all analysed substances, representative of the Adriatic River Basin District, have been determined at the basin-wide level, considering the structural similarity of karst aquifers as well as the hydrological conditions and flow dynamics within groundwater bodies, using simplified statistical methods, primarily the modified preselection method. This method identifies and excludes potentially contaminated samples before calculating the 90th percentile as the upper limit of ambient background concentration. These values are then compared with criteria values derived from drinking water standards or environmental protection goals to determine threshold values for risk assessment. Monitoring points are selected based on hydrogeological representativeness, prioritizing springs and abstraction sites with long-term data availability and ecological relevance. The selection of parameters follows national and EU guidelines, focusing on substances with known environmental or health impacts, and includes both naturally occurring and anthropogenic compounds.

In Croatia, the legal framework for artificial aquifer recharge and the discharge of treated wastewater into the underground is primarily governed by the Water Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023) and the Regulation on Emission Limit Values for Wastewater ("Official Gazette" No. 26/2020). The Water Act prohibits direct discharges of pollutants into groundwater, except in cases defined by specific regulations, and allows indirect discharges only under strict conditions. Indirect discharge is defined as the infiltration of treated wastewater through subsurface filtration layers, typically via soil or unsaturated zones. Such discharge is permitted only when alternative solutions are technically unfeasible or disproportionately costly, and when it is proven that the discharge will not negatively affect groundwater quality or the aquatic environment. The Regulation specifies which pollutants are strictly prohibited from entering groundwater and outlines the conditions under which treated wastewater may be infiltrated. However, it lacks detailed criteria and methodologies for conducting impact assessments of such discharges. The Decision on the Methodology of Combined Approach (2018) – issued by Croatian Waters – refers to emission limits and pollutant loads for discharges into karst systems, aligning them with criteria for indirect discharges. Despite these provisions, Croatia does not yet have a comprehensive regulatory framework that fully aligns with EU directives regarding managed aquifer recharge (MAR). The current legal instruments do not provide clear guidelines for evaluating risks to groundwater-dependent ecosystems or for designing monitoring systems. Therefore, the development of national criteria and technical guidance is necessary to ensure safe and sustainable implementation of MAR practices in Croatia.

Remediation of contaminated soil and/or groundwater is not specifically defined in any law or bylaw of the Republic of Croatia. In the River Basin Management Plan (RBMP) until 2027 ("Official Gazette" No. 84/2023), as well as in the Rulebook on conditions for establishing the zones of sanitary protection of water sources ("Official Gazette" No. 66/2011, 47/2013), remediation measures are linked to potential activities that may endanger groundwater. The RBMP outlines several key remediation measures for contaminated soil and groundwater, with particular attention to karst areas. These

measures include intensified efforts to close and rehabilitate official and illegal waste disposal sites, especially those heavily polluted with industrial waste. The RBMP emphasizes the need for improved monitoring and inventory of pollutants entering water systems, which is crucial for effective remediation. In karst regions, where groundwater is highly vulnerable, direct discharge of pollutants into groundwater is strictly prohibited. Additionally, the RBMP promotes the development of technical solutions that prevent contamination during flood events, particularly in former floodplain areas. Remediation measures in sanitary protection zones for karst water sources are defined in Article 7 of the 2011 Rulebook on conditions for establishing the zones of sanitary protection of water sources ("Official Gazette" No. 66/2011), which requires a formal Program of remediation measures for existing facilities and activities. It must include a list of polluters, priority actions, deadlines, costs, and responsible parties. In practice, this Program is frequently not implemented or is only partially enforced. In karst areas, where groundwater is highly vulnerable due to rapid infiltration and limited natural filtration, Article 3 emphasizes the need for detailed hydrogeological investigations, including assessments of fissured and cavernous aquifers. According to Article 23 of the 2013 amendments of this Rulebook ("Official Gazette" No. 47/2013), in Zone II of karst aquifers, agricultural and industrial activities are prohibited unless they follow ecological standards and water protection programs. Article 21 further restricts activities in Zone III, banning waste disposal, construction of polluting facilities, and pipeline installations unless strict water protection measures are in place. Exceptions, such as waste management centres, are allowed only under conditions outlined in Article 1, including impermeable construction, flood protection, and continuous monitoring.

According to Croatian legislation, the obligation to include sanitary protection zones of water sources in spatial planning documents is clearly defined in both the Water Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023) and the Rulebook on conditions for establishing the zones of sanitary protection of water sources ("Official Gazette" No. 66/2011, 47/2013). In the Water Act, Article 104, paragraph 3 stipulates that the competent local or regional authority must adopt a decision on the protection of water sources, which includes the delineation of sanitary protection zones. This decision must be based on a hydrogeology study and is binding for further planning and land use decisions. In the Water Act, Article 104, paragraph 5, it is stated: "Sanitary protection zones of water sources, which are defined by a formal decision, as well as areas reserved for sanitary protection zones for which no decision has been adopted, must be included in the spatial planning documents of the area in which these zones are located". Article 5 of the Rulebook outlines the required contents of the technical study, including maps, pollutant inventories, and proposed protective measures. These elements serve as the basis for spatial planning decisions and for implementing restrictions and remediation measures within the zones. The Rulebook, in Article 6, explicitly states: "Based on the study of sanitary protection zones of water sources, space reservation for sanitary protection zones may be implemented in spatial planning documents. This reservation shall be carried out in accordance with regulations on spatial planning and construction." This means that once the zones are defined through hydrogeological study and technical documentation, they must be incorporated into spatial plans to ensure legal protection and control of land use within these zones.

Following the adoption of a decision on sanitary protection zones of water sources by the representative body of a local or regional self-government unit, the zones must be incorporated into the relevant spatial planning documents of the area in which they are located. The timeline of this process depends on the procedures for amending and supplementing spatial plans by the respective local or regional authorities. Spatial plans must include the boundaries of individual sanitary protection zones, as well as a summary of the protection measures implemented within those zones. In essence, the legal obligation to include sanitary protection zones in municipal, city, and county

spatial plans is being fulfilled, but with varying dynamics. This means that it is not possible to define a precise timeframe within which the zones will be incorporated into spatial plans. This applies both to newly established sanitary protection zones and to updates of existing zones, which may occur, for example, due to changes in legal or regulatory frameworks.

Croatia's water legislation demonstrates an adequate enforcement capacity through a combination of legal mechanisms and institutional structures that enable the enactment and application of regulations. The Water Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023) establishes a comprehensive framework for managing water quality and quantity, protecting against harmful water impacts, and aligning with EU directives such as the Water Framework Directive (2000/60/EC) and the Urban Waste Water Treatment Directive (91/271/EEC). The Act empowers Croatian Waters as the central implementing body, responsible for issuing water Permits, monitoring compliance, and enforcing water protection measures. It also mandates the development of RBMP, which serve as binding instruments for planning and enforcement. The Water Management Financing Act ("Official Gazette" No. 153/2009, 90/2011, 56/2013, 154/2014, 119/2015, 120/2016, 127/2017, 66/2019, 36/2024) supports enforcement by ensuring financial sustainability. It defines water-related fees and contributions, including penalties for non-compliance, and outlines mechanisms for funding water infrastructure, remediation, and monitoring activities. Further enforcement tools are provided by the Regulation on Emission Limit Values for Wastewater ("Official Gazette" No. 26/2020), which sets strict thresholds for pollutants in industrial and municipal wastewater. It includes provisions for sampling, reporting, and penalties, and integrates EU standards for environmental protection. The Regulation also allows for temporary exemptions under controlled conditions, ensuring flexibility while maintaining environmental safeguards. The RBMP emphasizes the role of water Permits and Concession conditions as key legal instruments for regulating activities such as wastewater discharge and water abstraction. These are aligned with environmental protection goals and are subject to revision to ensure compliance with emission limits and ecological standards. Institutional capacity is reinforced through the integration of public water service providers, aiming to improve technical and financial sustainability and ensure effective implementation of infrastructure projects. Additionally, the RBMP sets clear deadlines for compliance with basic measures, such as the 2023 deadline for existing polluters to meet emission standards, and the 2024 deadline for temporary discharge Permits.

Croatia's water legislation provides a solid foundation for operational capacity, particularly in terms of human and financial resources needed for the implementation of water and wastewater policies. The Water Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023) establishes the institutional framework, assigning key responsibilities to Croatian Waters, a public body with legal authority to manage water resources, issue permits, conduct monitoring, and enforce regulations. Ministry of Environmental Protection and Green Transition plays a central role in coordinating water policy, aligning it with other sectors such as agriculture, health, and environmental protection. It is also responsible for strategic planning, legislative updates, and overseeing the implementation of EU directives. The RBMP acknowledges challenges in securing sufficient financial resources, especially for large-scale investments planned for the 2021–2030 period. To mitigate these risks, it proposes measures such as capital market research, communication strategies, and socio-economic studies on public willingness to pay for water services. Human resource capacity is supported through institutional strengthening, training, and certification systems for water guards and hydrogeological professionals, as well as through structured roles within Croatian Waters and local authorities. Financial capacity is reinforced by mechanisms for cost recovery, including water usage fees and environmental charges and by the obligation to prepare annual and multi-year investment programs, which are aligned with national and EU priorities. A wide range of bylaws and technical regulations

further support operational capacity. The Rulebook on Technical Requirements for Drainage Structures ("Official Gazette" No. 3/2011), which defines the design, construction, and maintenance standards for wastewater infrastructure. According to The Rulebook on Water Sampling and Testing ("Official Gazette" No. 125/2017) the register of legal entities performing public water supply activities is maintained. It stipulates that public water service providers, as well as other legal entities supplying water for human consumption (averaging more than 10 m^3 per day or serving more than 50 people), must be included in the register. This register is managed by the competent authority and serves as a basis for monitoring obligations, compliance verification, and reporting under the national water safety framework.

The Water Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023) assigns supervisory authority to the Ministry of Environmental Protection and Green Transition and Croatian Waters, which conduct inspections, issue water Permits, and oversee the implementation of RBMP. The Ministry maintains a registry of legal entities involved in public water supply, which supports targeted supervision and enforcement. In cases of environmental emergencies, special regulations govern the response and remediation, ensuring swift action to mitigate damage. Furthermore, the Water Act also regulates the role and significance of the State Inspectorate, which is responsible for supervision over the implementation of the Water Act and regulations adopted under it, including oversight of legal and natural persons performing water-related activities. The Inspectorate has the authority to conduct inspections, issue enforcement orders, and initiate misdemeanour proceedings in cases of non-compliance. This includes violations related to water pollution, unauthorized water use, and failure to meet technical or environmental standards. The Act also defines the legal basis for issuing penal measures, including fines and corrective actions for violations such as unauthorized discharges, failure to meet emission standards, or non-compliance with permit conditions. The Water Management Financing Act ("Official Gazette" No. 153/2009, 90/2011, 56/2013, 154/2014, 119/2015, 120/2016, 127/2017, 66/2019, 36/2024) complements this framework by specifying financial penalties for breaches and outlines fines depending on the severity of the violation. These sanctions apply to individuals and legal entities that fail to comply with obligations related to water use, wastewater discharge, or payment of water-related fees. The RBMP highlights the need for intensified monitoring and stricter control in areas where water abstraction exceeds permitted limits, indicating a proactive enforcement strategy.

International collaboration of the Republic of Croatia in a water sector is regulated by the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Helsinki Convention, Helsinki 1992) and the relevant Protocol on Waters and Health. For carrying out the Convention the Ministry of Environmental Protection and Green Transition is authorized. International collaboration on a Black Sea catchment area is regulated by the Convention on Cooperation for the Protection and Sustainable Use of Danube River (the Danube Convention, Sophia, 1994 – ratified in Croatian Parliament in 1996) and the Framework Agreement on Sava River Basin, Kranjska Gora, 2002 - ratified in Croatian Parliament in 2003) as well as the relevant Protocol on Navigation Regime. For carrying out the Convention on Cooperation for the Protection and Sustainable Use of Danube River and the Framework Agreement on Sava River Basin the Ministry of Environmental Protection and Green Transition is authorized. In the implementation of this framework agreement, an important operational role is played by Croatian Waters, as the technical body responsible for water resource management; the State Hydrometeorological Institute, which participates in the flood forecasting and warning system (Sava FFWS); and the Sava Commission, headquartered in Zagreb, which coordinates activities among the signatory countries. Collaboration on the Adriatic Sea catchment area is regulated by the Convention for the Protection of the Marine Environment and the Coastal Region of the

Mediterranean (Barcelona Convention) adopted in 1976, and revised in Barcelona, Spain, in 1995 as the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean and the Protocol for the Protection of the Mediterranean Sea against Pollution from Land-based Sources and Activities (Athens) adopted in 1980 and revised in 1995. For the execution of the Barcelona Convention, the Service for the Sea and Coastal Area of the Ministry of Economy is authorized. For the execution of the Protocol, the Ministry of Environmental Protection and Green Transition is responsible, particularly in relation to the Protocol on Integrated Coastal Zone Management (ICZM Protocol), the development of the national strategy for the management of the marine environment and coastal area, and the implementation of environmental policies arising from the Convention. The Republic of Croatia is also a signatory of the Convention on the Transboundary Effects of Industrial Accidents (Helsinki, 1992), and the authorized ministry is the Ministry of Environmental Protection and Green Transition. The Adriatic-Ionian Initiative (AII) was formally established as a political initiative at a conference held in Ancona, Italy in May 2000. Seven countries cooperate within the framework of AII: Albania, Bosnia & Herzegovina, Croatia, Greece, Italy, Slovenia and Serbia & Montenegro. The aim of AII is to link the coastal countries of the two seas for the purpose of cooperating in the development and safety of the whole area. The issue of environmental protection, which is central for socio economic development in the sub-region is the high sensitivity of the maritime and coastal areas of the closed Adriatic Sea. The Joint Commission for the Protection of the Waters of the Adriatic Sea and Coastal Areas from Pollution is also active. It was established in 1977 based on the 1974 Agreement between the former Yugoslavia and Italy, and its members are Croatia, Italy, Slovenia, and Montenegro. The coordination of activities is led by the Ministry of Environmental Protection and Green Transition. Representatives of other ministries also participate in its work, including those of foreign affairs, finance, agriculture, transport, culture, science, etc., as well as experts from relevant fields. The Republic of Croatia ratified the following bilateral international agreements/contracts related to the water management: Agreement between the Government of the Republic of Croatia and the Government of the Republic of Hungary on Water Management Relations" (Pecs, June, 1994); Contract between the Government of the Republic of Croatia and the Government of Bosnia and Herzegovina on Water Management Relations (Dubrovnik, July, 1996); Contract between the Government of the Republic of Croatia and the Government of the Republic of Slovenia on Water Management Relations" (Zagreb, October 1997); Contract between the Government of the Republic of Croatia and the Government of the Republic of Montenegro on Water Management Relations (Zagreb, September, 2008).

The legal framework does not fully account for the dynamic interactions between karst groundwater and surface water, nor does it adequately regulate the impacts of seasonal overexploitation, such as salinization in coastal aquifers. There is a lack of regulatory mechanisms to control water abstraction during dry periods, which increases the risk of salinization and ecological degradation. Cross-border cooperation on shared (transboundary) aquifers remains underdeveloped, with no binding legal instruments ensuring coordinated management. Vulnerability mapping and risk assessments are inconsistently applied and not aligned with standardized EU methodologies such as COST 620. There is no legal obligation to develop or apply conceptual and mathematical models for predicting pollution impacts on groundwater systems. The legal framework lacks enforceable measures for protecting groundwater-dependent ecosystems from cumulative pressures and does not ensure harmonized methodologies or consistent data quality across monitoring networks, nor does it mandate integration of ecological vulnerability into groundwater protection strategies. Furthermore, there is no targeted groundwater monitoring system capable of reliably assessing agricultural impacts, especially in karst areas where hydrogeological complexity demands specialized approaches. Although Croatia has

adopted EU directives and developed national methodologies, the determination of threshold values often lacks site-specific environmental criteria, especially for karst aquifers. The current approach relies heavily on background concentrations and precautionary principles but does not fully integrate environmental interactions or vulnerability. Furthermore, the absence of standardized procedures for setting environmental threshold values limits effective protection of groundwater-dependent ecosystems. These gaps highlight the need for more environmentally grounded and site-specific legal instruments. A significant deficiency in the Croatian legal framework is the lack of clear and comprehensive regulation governing the discharge of treated wastewater into the underground, particularly in sensitive karst regions. While EU directives recognize artificial aquifer recharge as a viable measure, Croatian regulations lack clear criteria and guidelines for assessing the impact of indirect discharges on groundwater and groundwater-dependent ecosystems. This is especially problematic in karst areas, where rapid water flow and limited natural filtration increase vulnerability. The absence of standardized procedures for environmental impact assessments and conceptual modelling further complicates risk evaluation. Therefore, a more robust, environmentally sensitive legal framework is needed to ensure sustainable groundwater protection in karst environments.

4 Policy, plans and principles

The Water Management Strategy (WMS) of the Republic of Croatia (“Official Gazette” No. 91/2008) emphasizes the importance of protecting groundwater resources, especially in karst regions, due to their vulnerability to pollution and their role in supplying drinking water. It promotes integrated water management aligned with EU directives, advocating for precautionary principles and the "polluter pays" approach. Key goals include reducing pollution from point and diffuse sources, improving wastewater treatment, and enhancing monitoring systems. The WMS calls for the gradual integration of local water supplies into public systems to ensure water quality control and public health safety. It also supports the rational use of water, reduction of losses in supply systems, and the introduction of economically sustainable water pricing. In karst areas, the WMS highlights the need for tailored technical solutions and stricter protection measures due to rapid groundwater flow and limited natural filtration. Pursuant to the objectives set forth in the Water Management Strategy (2008), competent authorities need to undertake measures for the delineation and establishment of sanitary protection zones around well fields and natural springs and need to ensure the implementation of appropriate protective measures in these zones.

The Water Management Strategy of Croatia (2008) is formally presented as a framework for coordinating sectoral strategies, including those related to agriculture, environment, tourism, traffic, and energy. It is partially harmonized with these sectors, with alignment most evident in strategic documents such as the Agriculture Strategy of the Republic of Croatia until 2030 (“Official Gazette” No. 26/2022), which addresses irrigation and pollution control in line with the EU Nitrates Directive or the Spatial Development Strategy of the Republic of Croatia (“Official Gazette” No. 106/2017). The Sustainable Tourism Development Strategy of the Republic of Croatia until 2030 emphasizes water supply and wastewater infrastructure in coastal areas, reflecting seasonal demands. The Energy Development Strategy recognizes the strategic role of hydropower and calls for alignment with bilateral agreements for transboundary projects. It is important to emphasize that the Water Management Strategy was adopted in 2008, whereas other relevant sectoral strategies have been

enacted more recently (from 2017 onward), which may hinder the establishment of coherent and effective cross-sectoral policy integration.

The National Development Strategy of the Republic of Croatia until 2030 (“Official Gazette” No. 13/2021) integrates environmental sustainability and resource protection across multiple strategic goals, but it does not explicitly or systematically address the impacts of economic sectors on groundwater or groundwater-dependent ecosystems. The strategy emphasizes green and digital transitions, climate neutrality, and sustainable resource management, particularly under Strategic Goal 8: "Ecological and energy transition for climate neutrality" and Strategic Goal 9: "Food self-sufficiency and development of the bioeconomy". It acknowledges the importance of integrated planning and cross-sectoral coordination. The Agriculture Strategy of the Republic of Croatia until 2030 (“Official Gazette” No. 26/2022) is focused on sustainable water use in agricultural production. It promotes improved access to irrigation and increased efficiency in water use, particularly in karst areas where groundwater is the main source. The strategy supports environmentally friendly practices and encourages the transition to organic farming, which indirectly contributes to reducing groundwater pollution from agrochemicals. It aligns with climate and environmental goals, however it does not explicitly define groundwater as a vulnerable resource nor establish targeted measures for its protection beyond general water management improvements. The Energy Development Strategy of the Republic of Croatia until 2030 with an outlook to 2050 (“Official Gazette” No. 25/2020), together with the Revised National Energy and Climate Plan (NECP), promotes sustainable energy development but only indirectly addresses groundwater protection. These strategies emphasize the expansion of renewable energy sources, especially hydropower, and the improvement of energy infrastructure. Groundwater is not explicitly identified as a vulnerable resource nor are there targeted safeguards for its protection. These strategies rely on compliance with EU environmental directives, which certainly include groundwater protection, but do not mainstream groundwater considerations into energy planning. The Spatial Development Strategy of the Republic of Croatia (“Official Gazette” No. 106/2017) recognizes groundwater as a strategic natural resource and emphasizes its protection within the broader framework of sustainable spatial planning. It highlights that nearly 90% of water used for public supply is abstracted from aquifers, underscoring the importance of safeguarding groundwater reserves, especially in karst regions. The strategy promotes integrated land use planning that considers hydrogeological characteristics and supports the delineation of sanitary protection zones around springs. However, while groundwater is acknowledged as critical, the strategy does not provide operational mechanisms for its protection across all sectors, relying instead on alignment with environmental legislation and planning instruments. The Waste Management Plan of the Republic of Croatia for the period 2023–2028 (“Official Gazette” No. 84/2023) addresses groundwater protection through its emphasis on environmentally sound waste treatment and disposal. It promotes the reduction of landfill use and the remediation of “hot spots,” which are often located within the catchment areas of important springs, especially in karst areas. The plan supports the development of infrastructure that minimizes leachate risks and aligns with EU directives on waste and water protection. Although groundwater is not the central focus, the plan integrates its protection through broader environmental and public health objectives, particularly in relation to hazardous waste and wastewater sludge management. Transport Development Strategy of the Republic of Croatia (2017–2030) (“Official Gazette” No. 84/2017) emphasizes the need for environmentally responsible planning and implementation of transport infrastructure, particularly in karst. Strategic Environmental Impact Assessments (SEIA) are mandated for all major projects, ensuring that groundwater protection is integrated into transport development. The Sustainable Tourism Development Strategy of the Republic of Croatia until 2030 (“Official Gazette” No. 2/2023) emphasizes the importance of

preserving natural resources as part of its broader environmental goals. It identifies the negative impacts of tourism on the environment and promotes sustainable spatial planning and infrastructure development to mitigate risks, particularly in ecologically sensitive areas such as karst terrains. Measures include reducing pollution, promoting circular economy principles, and integrating environmental impact assessments into tourism planning.

The River Basin Management Plan (RBMP) until 2027 ("Official Gazette" No. 84/2023) outlines a comprehensive framework for the protection and sustainable management of groundwater resources and associated ecosystems. Groundwater bodies are delineated based on hydrogeological and hydrogeochemical criteria, ensuring assessment of both quantitative and chemical status. The plan integrates the requirements of the EU Groundwater Directive (2006/118/EC, 2014/80/EU), emphasizing the prevention of pollution and degradation of groundwater quality. Direct discharges of pollutants into groundwater are prohibited, with rare exceptions allowed only for treated wastewater under risk assessments and enhanced monitoring protocols. The plan also addresses the vulnerability of coastal aquifers to salinization in karst regions, where cumulative effects of reduced recharge and seawater intrusion pose significant risks. Groundwater-dependent ecosystems (GWDE) are explicitly considered in the assessment of groundwater status. Monitoring programs are strengthened to detect subtle changes in groundwater levels and quality, especially near sensitive habitats. Furthermore, the RBMP promotes the development of methodologies for evaluating the effectiveness of protective measures for GWDEs. This includes criteria for assessing salinization impacts and the role of groundwater in sustaining biodiversity. The integration of climate adaptation strategies highlights the increasing importance of groundwater quality and quantity resilience amid changing hydrological regimes.

The River Basin Management Plan (RBMP) until 2027 ("Official Gazette" No. 84/2023) identifies several key challenges related to groundwater, including over-abstraction, pollution, and the vulnerability of karst aquifers. The plan includes a test of environmental connectivity, which is an integral part of the classification tests for assessing the chemical and quantitative status of groundwater bodies according to CIS Guidance No. 18 (Commission of the European Communities, 2009), confirming that groundwater abstraction does not adversely affect surface water bodies or terrestrial ecosystems reliant on groundwater flows. However, certain local challenges remain underrepresented. For example, diffuse pollution from agriculture and the cumulative impacts of tourism-related water use in coastal areas are not comprehensively addressed. Specific measures for karst areas are defined with notable precision. The plan recognizes the unique hydrogeological dynamics of the Dinaric karst, including rapid flow velocities, short residence times, and episodic turbidity events following heavy rainfall. Monitoring protocols in karst regions incorporate statistical trend analyses and background level assessments for key parameters such as sulphates, chlorides, and electrical conductivity.

The Water Management Strategy (WMS) of the Republic of Croatia ("Official Gazette" No. 91/2008) emphasizes the enhancement of monitoring systems for both groundwater and surface waters, including transitional and coastal waters, aligning with EU directives. The WMS outlines the need for spatial harmonization of monitoring networks, the adoption of new technical standards, and the implementation of automated data collection and transmission systems. A key component is the integration of water quality indicators into national databases and the establishment of regular reporting mechanisms, such as annual water status reports and six-year river basin management plans. Pollution protection measures are systematically addressed through improved surveillance of point and diffuse pollution sources. This includes industrial discharges, urban wastewater, agricultural

runoff, and traffic-related contaminants. The WMS also calls for the development of quality assurance protocols and the strengthening of laboratory capacities to ensure reliable water quality assessments. Although the WMS recognizes the hydrogeological complexity of karst regions, it does not explicitly define targeted protective measures for groundwater-dependent ecosystems in these areas. However, it does propose the adaptation of monitoring programs to protected and sensitive zones, which implicitly includes karst systems.

The River Basin Management Plan (RBMP) until 2027 ("Official Gazette" No. 84/2023) recognizes the hydraulic connectivity between groundwater and surface water systems, in both the Pannonian and Dinaric karst regions. In karst regions, surface water infiltrates through fractured carbonate formations, re-emerges at springs, and contributes to surface flows, forming a dynamic exchange system. To assess and manage this connectivity, the plan introduces the "Surface Water Test," which evaluates the chemical status of groundwater bodies in relation to their impact on associated surface waters. This test includes cross-referencing critical parameters (e.g., nitrates, phosphates, heavy metals) between groundwater and surface water monitoring datasets. The step ahead to integrated monitoring of groundwater and surface waters is achieved through harmonized sampling protocols, shared analytical parameters, and spatially coordinated monitoring stations. Common protection goals are defined through unified environmental objectives, combining chemical and quantitative criteria for groundwater with ecological and chemical criteria for surface waters. These objectives are aligned with EU Water Framework Directive standards and are operationalized through targeted measures, including stricter controls on wastewater discharges, enhanced monitoring of industrial and municipal effluents, and the minimization of direct discharges into groundwater.

In Croatia, the system of public financing in the water and agricultural sectors generally supports the sustainable use of (ground) water, although certain structural weaknesses may, under specific circumstances, create indirect pressures on water resources. According to the Water Act (Official Gazette No. 66/2019, 84/2021, 47/2023) and the Water Management Financing Act (Official Gazette No. 153/2009, 36/2024), the costs of water use and protection are based on the principles of the polluter pays and cost recovery, thereby promoting rational and responsible use of water resources. The River Basin Management Plan until 2027 (Official Gazette No. 84/2023) highlights the need to reduce pressures from agriculture, particularly those related to nitrate and pesticide pollution that threaten groundwater.

In agriculture, through the Common Agricultural Policy (CAP) and the National Strategic Plan for CAP 2023-2027 (Regulation on the Implementation of Direct Support to Agriculture and IACS Measures, Official Gazette No. 31/2025), eco-schemes and green interventions are introduced to direct financial resources towards environmentally friendly practices. One of the concrete schemes is the High Nature Value (HNV) Grassland Conservation Scheme, applied to areas registered in the ARKOD system, enabling beneficiaries to receive compensation for additional costs and income loss due to ecological commitments. Within this scheme, the use of mineral and organic fertilizers, pesticides, grassland reseeding, and land reclamation works are prohibited. The level of support in mountain and hilly regions ranges from EUR 229.50 to 280.50 per hectare, depending on regional conditions. Eco-schemes also frequently require training, advisory activities, and the keeping of records on compliance obligations. Additionally, within eco-schemes, the Ministry of Agriculture, Forestry and Fisheries has introduced specific incentives for the conservation of HNV grasslands, which are often located in karst areas, thereby contributing to the protection of habitats of plant and animal species adapted to seasonal or permanent karst conditions. Such grasslands must be maintained without fertilizers, pesticides, or land reclamation works, reducing risks of groundwater pollution and degradation.

However, parts of the support system in the livestock and intensive crop production sectors can still indirectly increase pressure on groundwater, particularly in areas lacking adequate infrastructure for manure and liquid waste management. As noted earlier, insufficiently controlled irrigation during drought periods may lead to excessive abstraction from local sources, although such cases are rare and regulated under the Croatian Waters permitting system (e.g. groundwater abstraction licenses). Overall, most public subsidies and financial incentives, particularly those linked to eco-schemes, rural development, and environmental protection, contribute to the sustainable use of (ground) water. Nevertheless, in the future, it will be necessary to further strengthen cross-sectoral control, integrate water objectives more systematically into agricultural policies, and focus especially on karst areas, where groundwater vulnerability is significantly higher.

5 Adherence to the WFD and GWD

The Water Management Strategy (WMS) of the Republic of Croatia ("Official Gazette" No. 91/2008) demonstrates a high level of alignment with the requirements of the Water Framework Directive (WFD) and the Groundwater Directive (GWD). It adopts the WFD's core objective of achieving "good status" for all surface and groundwater bodies, integrating ecological and chemical criteria into water quality assessments. The WMS emphasizes sustainable water use through integrated river basin management, reflecting the WFD's holistic approach. It also incorporates the principle of "polluter pays" and outlines economic instruments such as water pricing and cost recovery, in line with Article 9 of the WFD. Groundwater protection is addressed through monitoring, delineation of protection zones, and control of hazardous substances, fulfilling GWD obligations. The WMS supports cross-sectoral coordination and public participation, essential elements of both directives. Furthermore, it includes provisions for monitoring, reporting, and adaptive management, ensuring compliance with EU environmental standards. In terms of strategic goals, the WMS mirrors the WFD's emphasis on long-term planning through its dual 15-year investment cycles, extending to 2038, and its commitment to reforming the water sector to meet EU standards. It also aligns with the GWD by prioritizing the protection of aquifers and improving institutional capacity for groundwater monitoring. The strategy's integration into spatial planning, environmental protection, and sectoral development (e.g. agriculture, energy, tourism) further reflects the WFD's call for water management to be embedded in broader policy frameworks.

The 2019 Water Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023) establishes the legal foundation for defining groundwater quality standards, including threshold values for pollutants. These are operationalized through the Regulation on Water Quality Standards ("Official Gazette" No. 96/2019, 20/2023, 50/2023), which specifies that threshold values must be determined to assess the chemical status of groundwater bodies and the risk of failing to meet environmental objectives. Regarding groundwater (GW) and groundwater dependent ecosystems (GWDE) quality standards and threshold values, Croatia has defined these through national legislation, particularly through the Regulation on Water Quality Standards that complements the Water Act. This includes standards for chemical status as mandated by the GWD, setting EU-wide pollutant limits with provisions for substances of national concern. A national methodology for determining groundwater and GWDE quality standards, including threshold values, exists and accommodates karst-specific conditions, given Croatia's hydrogeological characteristics, but specific technical details or assigned national

guidelines for karst areas are embedded in by-laws and are supported by systematic monitoring and scientific input from institutions like the Water Institute Josip Juraj Strossmayer.

The Regulation aligns with Article 3 of the Groundwater Directive (2006/118/EC), incorporating both EU-wide standards and nationally derived values for substances of concern. These legal instruments define groundwater quality standards as concentrations that should not be exceeded to protect human health and the environment. The methodology adopted in Croatia is embedded in the national River Basin Management Plan (RBMP) until 2027 ("Official Gazette" No. 84/2023) and aligned with EU directives. It integrates background concentrations, criteria values, and risk assessment procedures, following the Common Implementation Strategy (CIS) Guidance No. 18 and No. 26, and incorporates the tiered approach from the international scientific project, funded under the Sixth Framework Programme of the European Union (FP6), titled "Background cRiteria for the IDentification of Groundwater thrEsholds" (BRIDGE), allowing for the derivation of threshold values from either background concentrations or environmental/usage criteria. Essentially, threshold values are derived either from environmental quality standards or from drinking water standards, depending on the intended use and/or proved interactions between groundwater and aquatic and terrestrial ecosystems, within a groundwater body or at its boundary. This ensures that the classification of chemical status and risk assessment is scientifically robust and legally compliant. For karst systems, this approach further accounts for natural geochemical variability and limited monitoring data. In cases where background concentrations exceed regulatory limits due to natural conditions, these values are used as reference thresholds to avoid misclassification of chemical status. Threshold values are established based on hydrogeological conceptual models and statistical analysis of monitoring data, with special attention to naturally occurring substances such as arsenic and iron. The Croatian approach distinguishes between substances of anthropogenic origin and those of geogenic origin, recommending site-specific thresholds when necessary. Furthermore, the threshold values derivation procedure is based on precautionary principle and introduces safety factors when comparing measured concentrations with threshold values, particularly in drinking water protected areas.

In Croatia, the national regulatory framework concerning areas designated for the abstraction of water intended for human consumption exhibits a degree of conceptual ambiguity. While the 2019 Water Act ("Official Gazette" No. 66/2019, 84/2021, 47/2023) and the national River Basin Management Plan (RBMP) until 2027 ("Official Gazette" No. 84/2023) recognize sanitary protection zones around springs and well fields, they do not fully incorporate the broader concept of groundwater bodies as defined by the EU Water Framework Directive (WFD). Groundwater bodies are assessed for their chemical and quantitative status, but the protection of drinking water resources is operationalized through these sanitary protection zones rather than through the designation of entire groundwater bodies as drinking water protected areas. This may lead to a misinterpretation whereby only sanitary zones are officially registered as protected areas, excluding the groundwater bodies themselves. Hence, the relationship between groundwater bodies and sanitary protection zones remains undefined in Croatian legislation. Although sanitary zones serve as tools for targeted protection, their delineation does not substitute for the identification of water bodies intended for human consumption, following the requirements of the WFD. Moreover, the assessment of chemical status in Croatia includes specific tests, such as the "DWPA test" (Drinking Water Protection Area), which evaluates compliance with threshold concentrations and trends in pollutants across the whole groundwater body. Additionally, Croatia has designated strategic groundwater reserves for current or future use, which are considered protected areas under the Water Management Strategy (WMS) of the Republic of Croatia ("Official Gazette" No. 91/2008). However, the lack of integration between these reserves and the WFD's conceptual framework further complicates the regulatory landscape.

Overall, the Croatian approach emphasizes sanitary protection zones but falls short of aligning fully with the WFD's requirement to designate entire groundwater bodies for drinking water abstraction.

6 Knowledge, information and awareness

Karst areas and their specific challenges are insufficiently addressed within the framework of the Water Framework Directive (WFD) and the Groundwater Directive (GWD), which poses significant obstacles to the effective implementation of key provisions, such as the prohibition of direct discharges into groundwater. Additionally, the lack of adequate monitoring data on groundwater quantity undermines the reliability of groundwater budgeting. To address this, major karst springs should be equipped with overflow discharge measurements in addition to abstraction volume monitoring, and water Permit holders must be required to report abstracted quantities within an optimally defined reporting timeframe.

Monitoring activities in Croatia encompass several aspects of water management, including surface and groundwater quality, water quantity (surface flow and, to a limited extent, overflow from karst springs), water abstraction volumes, spring discharge capacity, ecological flow, and key ecological indicators. These activities are primarily aligned with the requirements of relevant EU directives, notably the Water Framework Directive (WFD).

Water quality monitoring covers both chemical and ecological status of surface and groundwater bodies, implemented through surveillance, operational, and research monitoring programmes aimed at assessing water status, identifying long-term trends, evaluating risks, and responding to pollution incidents.

Water abstraction data collection is a legal obligation of Water Use Permit holders. For public water supply purposes, utility companies submit daily abstraction data to the Croatian Waters database, with monthly reporting intervals. Other users, including those in agriculture and industry, report total monthly or annual abstraction volumes. However, unauthorized or illegal abstraction remains a significant issue, particularly in coastal karst regions.

Ecological flow monitoring is conducted periodically to support the maintenance and restoration of freshwater ecosystems, in accordance with EU biodiversity strategies and WFD ecological flow requirements.

Key ecological indicators include the conservation status of species, habitat condition, and ecosystem service metrics, with partial data coverage available for forested areas, agricultural ecosystems, and wetlands.

Ongoing monitoring programs:

- Surveillance Monitoring: Focuses on assessing long-term natural and anthropogenic changes; includes chemical and ecological analyses of waters; temporal resolution is long-term, spatially distributed in river basin districts.
- Operational Monitoring: Targets surface waters and groundwater bodies at risk; monitors priority substances and pollutant trends; higher temporal resolution for detecting changes due to measures.

- Research Monitoring: Used for identifying unknown pollution causes, sudden pollution events; more intensive temporal and spatial resolutions during investigations.
- Water Watch List Monitoring: Tracks emerging pollutants as mandated by EU directives over periods of at least one year at selected stations.

Variables monitored include physical-chemical parameters (nutrients, heavy metals, pesticides), biological indicators (macroinvertebrates, fish, ecological status), hydrological variables (discharge, water levels), and abstractions by sector. Specific monitoring networks supply comprehensive data for river basin management plans and status assessments.

Drinking water monitoring is conducted at all springs and wells utilized for public water supply purposes, in accordance with national regulations and EU drinking water standards.

Water quantity monitoring is carried out through surface water gauging stations operated by the State Hydrometeorological Service (DHMZ) and Croatian Waters, as well as through groundwater monitoring stations located at springs and wells. Additionally, data on abstracted water volumes are collected from Water Use Permit holders.

Here is a more detailed breakdown of water monitoring data and ongoing programs in Croatia, organized into tables with specific data points where available:

Table 1 Water Quality Monitoring

Monitoring Aspect	Data Available	Monitoring Program	Variables Monitored	Time Resolution	Spatial Coverage
Surface and Groundwater	Chemical and biological status	Surveillance, Operational,	Nutrients (N, P), heavy metals, priority substance	Seasonal (4 time per year) to annual	River basin districts, coastal and inland
	quality data for sea and inland waters	Research Monitoring	Microbiological (*E. coli, enterococci*), physical-chem		sampling stations (~1130 coastal and inland)
Bathing Water Quality	Excellent quality at >95% coastal sites (2019-23)	Bathing Water Monitoring	Microbiological parameters (*E. coli, enterococci*)	weekly sampling May-Oct	7 coastal counties and local self-gov units

Monitoring Aspect	Data Available	Monitoring Program	Variables Monitored	Time Resolution	Spatial Coverage
Drinking Water Quality	Raw and treated water quality from springs	Raw water and Distribution	Physical-chemical and microbiological parameters	Daily (distribution), annual (raw water)	Major water supply sources

Table 2 Water Quantity Monitoring

Aspect	Data Available	Monitoring Program	Variables Monitored	Time Resolution	Spatial Coverage
Surface Flows	Flow regime	Ecological/Groundwater Flow Monitoring	Flow volumes, water temperature, habitat condition	Continuous or event-based	Selected rivers, protected areas
Abstraction Volumes	Water supply	Water Use Monitoring	Volume abstracted (m^3/day)	Daily	Surface and groundwater bodies
	Industry Agriculture		Volume abstracted (m^3/year/season)	Seasonal to annual	
Illegal Abstraction	Partial data, ongoing upgrading	Enforcement and Compliance	Reported incidents, estimated volumes	Ad hoc	National and local scales

Table 3 Key Ecological Indicators Monitoring

Aspect	Data Available	Monitoring Program	Variables Monitored	Time Resolution	Spatial Coverage
Biodiversity and Habitat	Species richness, habitat status	Ecosystem and biodiversity monitoring	Vegetation types, species abundance, habitat conditions	Periodic	National, protected areas, freshwater and coastal ecosystems

The monitoring carried out by Croatian Waters and the Water Institute Josip Juraj Strossmayer is part of their compliance with EU directives and national environmental legislation, involving coordinated efforts among environmental institutes, water management agencies, and specialized research organizations.

Data, information, and expert knowledge on groundwater and groundwater-dependent ecosystems (GWDE) in the karst areas of Croatia are partially publicly available, through several official institutions, digital geoportals, and published reports. The level of accessibility depends on the type of information, its format, and the institution responsible for data collection and maintenance.

Limitations and practical notes: raw time series of groundwater quality data are not always openly available per monitoring site. They are often aggregated in annual reports or shown through interactive geoportals without the option of bulk download.

Information on groundwater-dependent ecosystems (GWDE) is scattered across various sources: in annexes to the River Basin Management Plan, within Bioportal (habitat types, Natura 2000 areas), and in national park management plans. A unified national database or portal dedicated specifically to GWDE does not currently exist.

Information on groundwater in Croatia is partly shared among public agencies, but the level of data exchange and coordination between public institutions, as well as between the public and private sectors, remains uneven and only partially systematic.

The exchange of environmental and water-related data among public institutions is primarily governed by the Water Act (Official Gazette, No. 66/2019, 84/2021, 47/2023) and by the INSPIRE Directive (2007/2/EC), implemented through the National Spatial Data Infrastructure (NIPP). This framework enables access to spatial datasets via open web services (WMS/WFS), mainly managed by Croatian Waters and the Ministry of Environmental Protection and Green Transition. Additionally, Croatia has enacted the Act on the Right of Access to Information (Official Gazette, No. 25/2013, 85/2015, 69/2022), which transposes the EU Directive 2003/4/EC on public access to environmental information into national legislation. This law guarantees every citizen the right to obtain information held by public authorities, including data on water quality, monitoring networks, and groundwater protection zones. It also obliges institutions to proactively publish environmental data and to ensure interoperability through the national open-data portal (https://pristupinfo.hr).

Croatian Waters is the competent authority responsible for the management and dissemination of all data related to water quality and quantity. The State Hydrometeorological Service (DHMZ), in cooperation with Croatian Waters, is tasked with the acquisition of water quantity data, while Croatian Waters, in collaboration with the Water Institute Josip Juraj Strossmayer, is responsible for the acquisition and management of water quality data

At the institutional level, Croatian Waters, the Croatian Institute of Public Health (CIPH), and the Croatian Meteorological and Hydrological Service (DHMZ) exchange data through formal reporting mechanisms under the Water Framework Directive (WFD) and through the national environmental information system. However, data exchange across sectors remains fragmented. The private sector and local utilities often rely on summary reports rather than direct access to raw datasets (e.g., continuous groundwater monitoring series or spatial data on karst aquifers). While inter-agency cooperation is supported by open data initiatives and formal agreements under NIPP and INSPIRE, structured and interoperable data sharing between public authorities, research institutions, and private operators is still limited.

Gaps and limitations:

- there is a notable deficiency in staffing and organizational capacity, particularly regarding the collection and management of groundwater quantity data. Currently, data on abstracted water used for public supply is primarily collected for the purpose of calculating water usage fees, rather than for comprehensive resource management. For the development of an accurate groundwater budget, it is essential to obtain overflow discharge data from karst springs, as well as precise daily abstraction volumes from all water users, including those in irrigation and industrial sectors. Given the pronounced seasonal variability characteristic of karst groundwater systems, such data are indispensable for conducting reliable hydrological analyses and ensuring sustainable water resource planning;
- there is no single national data platform integrating all groundwater and groundwater-dependent ecosystem (GWDE) datasets, particularly those relevant to karst regions: technical and organizational differences between institutions (e.g., metadata standards, GIS formats) hinder full interoperability; private entities, including consultants, utilities, and land users, face barriers in accessing detailed or real-time groundwater data.

Croatia has established a strong legal basis for transparency and open access to environmental information, in line with EU requirements, and maintains several functional data-sharing mechanisms within the public sector. Nevertheless, the practical exchange of groundwater data across institutions and with private stakeholders remains limited, especially for detailed monitoring and karst-related datasets. Further integration of NIPP, the open-data portal, and sectoral information systems would enhance transparency, efficiency, and the sustainable management of groundwater resources.

7 Socio-economic setting and challenges

In the karst regions of Croatia, several challenges related to groundwater management have been identified at both national and regional levels. When addressed systematically, these challenges can serve as catalysts for developing a more effective and integrated water management system.

Groundwater in Croatia, particularly within karst regions, is predominantly utilized for public water supply, accounting for approximately 90% of total use, while the remaining 10% is allocated to irrigation and industrial purposes. In the past decade, there has been a noticeable increase in groundwater use for industrial and agricultural activities in coastal areas, largely driven by the lower cost of groundwater, especially within the tourism sector. However, due to insufficient quantification - particularly in agricultural use - comprehensive and reliable analyses of groundwater usage remain challenging.

Uncontrolled or illegal waste disposal in karst areas, particularly hazardous or industrial waste, poses a serious threat to groundwater. Leachates from such sites can quickly contaminate subsurface layers, which in karst terrains are often directly connected with surface waters and sinking streams. An additional problem stems from numerous facilities dating back to the socialist period, such as silos, industrial warehouses and former production halls, which, after privatization, have often been abandoned or poorly monitored. In depopulated and deindustrialized regions, these facilities have become vulnerable sites for manipulation and illegal waste storage without adequate environmental control.

Another threat to karst water systems is the construction of new reservoirs, such as the expansion of Kruščica Lake on the Lika River. During filling and discharge cycles, water levels fluctuate significantly, which negatively affects flora and fauna as well as the stability of groundwater-dependent ecosystems and connected aquatic systems.

Further challenges include inconsistent availability of raw groundwater data and fragmented exchange of information between public agencies, the private sector and local governments. This reduces the capacity for timely and predictive water management. Weak coordination between sectors, together with limited technical capacity in smaller municipalities, further hinders the implementation of protection measures and sustainable groundwater governance.

Improved groundwater management in karst areas can be achieved through a combination of technical, institutional and participatory measures that may act as triggers for systemic change. One key step is the introduction of additional monitoring stations and sensors in karst aquifers, with emphasis on quantitative and chemical indicators. This would enable faster detection of changes caused by reservoirs or waste disposal and support early risk response.

It is also necessary to introduce stricter criteria for defining waste disposal locations in karst areas and ensure full public transparency in decision-making. Establishing a digital waste tracking system would allow the monitoring of waste from origin to final disposal, reducing opportunities for illegal activities. Another important step would be creating a unified national database on groundwater-dependent ecosystems (GWDE), integrating existing datasets, spatial layers and monitoring results to improve analysis, coordination and transparency.

Finally, greater public participation and access to information are essential. Regular publication of groundwater status reports, open access to GIS data and cooperation with civil society organizations can strengthen trust and improve environmental oversight.

In conclusion, groundwater management in Croatia's karst regions faces multiple challenges, from waste disposal and weak data exchange to infrastructure projects that disturb natural hydrological systems. Yet, these same challenges offer clear triggers for improvement through modernized monitoring, better regulation of waste management, integrated data systems and active public involvement.

Groundwater and groundwater-dependent ecosystems (GWDE) represent one of the most vital natural assets of the Dinaric karst area, shaping its hydrological, ecological and socio-economic systems. Their importance extends beyond water supply to include energy production, agriculture, tourism, and the preservation of biodiversity, thereby directly supporting both the economy and human well-being.

Drinking water supply and public health - karst aquifers form the backbone of local and regional water supply systems in Dalmatia, Lika, and Gorski Kotar. Springs and wellfields in karst areas provide drinking water to towns and settlements and therefore require strict sanitary protection zones and continuous quality monitoring. National reports confirm the scope of water sampling and the compliance of drinking water with health standards, as well as the role of sanitary inspection and public health institutes in risk assessment, highlighting the direct link between groundwater and public health.

Energy and water regime regulation - groundwater and surface waters in karst are hydraulically connected, making them essential for both hydropower systems and water regime management (droughts and floods). In Lika, particularly in the Lika and Gacka plains, existing and planned hydropower infrastructures (such as Kosinj/Senj 2 and related reservoir systems) rely on the water balance of karst catchments. These interventions are of significant economic importance for electricity production, but they also pose risks to the ecological status and groundwater-dependent ecosystems (GWDE) due to potential rapid water level fluctuations and changes in inflows to sinking streams and springs. Therefore, careful planning, monitoring, and operational adaptation are required.

Tourism, landscape values and cultural services - the Plitvice Lakes and Krka National Parks are world-renowned karst systems whose habitat diversity, travertine formation, and water purity depend directly on the groundwater regime. The parks carry out continuous hydrological and hydrochemical monitoring (in cooperation with DHMZ and Croatian Waters), while the preservation of aquatic habitats, including Natura 2000 types, represents the foundation of their tourist appeal and a key pillar of the local economy.

Agriculture and local economy - although irrigation in karst areas is limited, the quality and reliability of groundwater resources support food processing, fisheries in karst rivers and lakes, and rural tourism. Access to information on water status (HZJZ reports, geoportals, NIPP) and open hydrological data from DHMZ enhances transparency and enables more rational planning within the local economy.

Nature protection and Natura 2000 - the Bioportal database and management plans for protected areas emphasize that many key karst habitat types are directly or indirectly dependent on groundwater. Maintaining their favourable conservation status depends on the protection of springs, sinkholes, and underground flows, as well as on the limitation of pollution and hydrological disturbances.

The development of water supply infrastructure in Croatia is generally well advanced, particularly in urban and coastal areas, where public water supply coverage exceeds 90%. However, significant disparities remain in rural and mountainous regions, especially in the Dinaric karst area (including Lika, Dalmatia Hinterland, and parts of Gorski Kotar), where population dispersion, karstic terrain, and limited financial resources hinder network extension. In these areas, individual wells and local water systems are still common.

Sanitation infrastructure shows similar spatial inequalities. While urban agglomerations are largely connected to sewerage systems and wastewater treatment plants (WWTPs), smaller settlements often lack adequate collection and treatment. As of 2024, Croatia operates more than 200 WWTPs, but their capacities and levels of treatment vary widely. The implementation of EU Directive 91/271/EEC on Urban Wastewater Treatment has driven significant progress since EU accession, yet full compliance remains challenging, particularly for settlements below 2,000 population equivalent (PE).

Waste management has undergone restructuring since the introduction of the 2017 Waste Management Plan and establishment of county-level waste management centres. However, in karst and remote rural regions, illegal dumping and insufficient recycling infrastructure remain serious issues that indirectly threaten groundwater quality. Landfills that are not yet remediated continue to pose local environmental risks, especially where natural karst permeability increases the potential for contamination transfer to aquifers.

Overall, the water supply system in Croatia is moderately to highly developed, while wastewater and waste management systems are in the medium stage of development, with marked regional disparities. Further investment in rural and karst areas, combined with integrated management of water, wastewater and solid waste systems, remains crucial for achieving national and transboundary groundwater protection goals under the DIKTAS framework.

The Croatian part of the Dinaric region is characterized by pronounced depopulation, population ageing, and strong tourism seasonality, as well as spatial imbalances between coastal and inland areas.

Economic activity is concentrated along the coast, while rural and mountainous areas are marked by low population density, underdeveloped infrastructure, and limited administrative capacities. Tourism, as the dominant sector, causes seasonal peaks in water demand; it increases the risk of saline intrusion in coastal aquifers and puts pressure on wastewater and treatment systems. Agriculture is mostly fragmented and low-intensity; diffuse nitrate and pesticide pollution continues to threaten karst aquifers, particularly in areas without public sewerage. Industrial and extractive activities are localized, but they can significantly affect the hydrodynamics and quality of groundwater in karst zones. Water supply infrastructure is relatively well developed, while wastewater collection and treatment systems lag behind, especially in small and dispersed settlements. Unregulated and illegal waste disposal sites represent the greatest local risk to groundwater and groundwater-dependent ecosystems (GWDE).

Macro-economic policies, including the National Development Strategy 2030, the River Basin Management Plan 2022–2027, and the CAP Strategic Plan 2023–2027, are broadly aligned with EU sustainable water management goals; however, implementation challenges remain significant in karst areas.

Quantitative and qualitative pressures on groundwater in the Croatian Dinaric region are assessed as medium to high, with a gradual improving trend due to planned investments and strengthened environmental policies.

Long-term protection of groundwater and GWDE depends on strengthening local capacities, introducing decentralized wastewater solutions, and ensuring better coordination among tourism, agriculture, and spatial planning policies.

In Croatia, a developed legislative and institutional framework for water management exists, based on the Water Act (Official Gazette 66/2019, 84/2021, 47/2023), the River Basin Management Plan 2022–2027, and the implementation of the EU Water Framework Directive (2000/60/EC). The key institutions, the Ministry of Environmental Protection and Green Transition and Croatian Waters, possess professional capacity, experience, and a stable financing system, and demonstrate a high level of alignment with European standards and obligations. Political leadership at the national level is generally supportive of effective groundwater management, as it ensures continuity of strategic documents, international cooperation (for example DIKTAS, UNECE Water Convention), and participation in EU funding programs. However, the implementation level, especially in karst and rural areas, faces limited administrative capacities, insufficient technical resources, and weaker coordination between sectors such as water, agriculture, tourism, and waste management. Horizontal cooperation between ministries, local authorities, and non-governmental organizations exists but is often fragmented and dependent on EU-funded projects. Despite these limitations, awareness of the importance of groundwater among decision-makers, professionals, and the public is gradually increasing thanks to the activities of Croatian Waters, the Croatian Institute of Public Health, and organizations such as WWF Adria and Zelena akcija. The digitalization of systems (Water Information System, NIPP/INSPIRE) and growing data transparency further contribute to more accountable management and supervision of groundwater resources. Overall, governance and political leadership in Croatia can be assessed as moderately conducive to groundwater management, with significant potential for improvement at the local level through capacity building, stronger cross-sectoral cooperation, and more active public participation.

In the coming years, several development trends and investments in the wider economy are likely to significantly affect groundwater in the Dinaric karst region, particularly in the counties of Istria, Primorje-Gorski Kotar, Lika-Senj, Zadar, Šibenik-Knin, and Dubrovnik-Neretva.

Coal and energy transition (Istria County) - the Plomin thermal power plant, located in Istria, remains the only active coal-fired power station in Croatia. Plans for its gradual phase-out within national climate and energy transition policies will influence the national energy mix and may increase pressure on alternative sources of energy such as hydropower, natural gas, and renewables, which partly rely on karstic water resources. Integrated planning and strict environmental monitoring are therefore crucial for this region.

Oil refining industry (Primorje-Gorski Kotar County) - the INA Rijeka refinery resumed production in 2024 after a major investment cycle aimed at improving energy efficiency; modernization may reduce emissions but requires continuous monitoring of groundwater and drainage systems. In the same county, the EU is financing the remediation of the old hazardous industrial waste landfill at Marinići, which directly benefits local aquifers.

Hydropower (Kosinj/Senj 2, Lika-Senj County) - the Kosinj project, part of the HES Senj 2 system, foresees new reservoirs and dams on the Lika River. Changes in flow regimes, infiltration, and groundwater levels are likely within karst aquifers and related springs, making hydrogeological supervision, ecological flow regulation, and protection zones essential. The project is currently in its pre-construction phase and has national strategic importance for energy production.

Planned lithium hydroxide processing plant (Lika-Senj County) - a private investor plans to build a plant in Gospić for processing lithium carbonate into lithium hydroxide, with an annual capacity of around 12,500 tonnes and full operation expected in 2025. Although the investor and local authorities claim minimal environmental impact, the plant's location in a karst terrain and near Natura 2000 sites poses

high potential risks. The absence of a formal environmental impact assessment increases concern. Independent hydrogeological studies, groundwater monitoring, and full data transparency are strongly recommended to ensure compliance with environmental and water protection standards, given the region's significance for drinking water reserves.

Fish processing and wastewater (Zadar County) - major fish processing plants, such as Mardešić in Sali and Cromaris in Zadar, discharge industrial wastewater with high organic load, fats, and salinity. If treatment and discharge are inadequate, they can degrade coastal karst aquifers. Several WWTP reconstruction projects are ongoing, supported by EU funding. Strict supervision of technological wastewater and collaboration with local utilities are required. Additionally, a new fish waste and fish meal processing facility is planned, which could reduce illegal waste disposal but may increase wastewater loads.

Industrial legacy (Šibenik-Knin County) - historical pollution sources, such as the former TEF Šibenik industrial complex, continue to affect sediments and the coastal environment. Elevated metal concentrations near the former site highlight the need for ongoing remediation and monitoring, especially given the rapid subsurface water transport typical of karst terrain.

Ports and maritime transport (Dubrovnik-Neretva County) - the Port of Ploče and related maritime operations present risks from ballast waters and hazardous substances. Studies emphasize the need for stricter management of discharges and prevention of invasive species introduction. EU-supported wastewater projects and ESG initiatives in Dubrovnik reduce pressures, but continued monitoring is essential, particularly in the Neretva Delta and coastal karst zones.

Municipal wastewater and tourism (coastal regions) - across multiple coastal agglomerations wastewater systems are being upgraded with EU support, positively influencing groundwater protection. However, seasonal peaks from tourism still increase loads during summer months. Systems must be designed for maximum seasonal capacity, while decentralized wastewater treatment should be developed for smaller settlements. Overall, the continuous growth of mass tourism and the steady increase in the number of tourist arrivals represent a lasting source of pressure and an intensification of the ecological footprint across all these counties, which together form the karst region of Croatia.

8 National SWOT analysis

Strengths

- Strong institutional framework with national bodies like Croatian Waters and Ministry of Environmental Protection and Green Transition.
- Alignment of national legislation with EU directives (WFD, GWD).
- Comprehensive River Basin Management Plan with karst-specific methodologies.
- Established sanitary protection zones around springs and wellfields.
- Functional monitoring systems for water quality, abstraction, and ecological flows.
- Active participation in international water conventions and bilateral agreements.
- Integration of groundwater (GW) protection into spatial planning and sectoral strategies.
- Public health institutions conduct regular drinking water quality assessments.

- Eco-schemes and CAP incentives promote sustainable agricultural practices in karst areas.
- High awareness and expertise among scientific and professional communities.

Weaknesses

- Fragmented horizontal coordination between sectors (e.g., agriculture, tourism, energy).
- Uneven operational capacity at local levels, especially in rural areas.
- Lack of institutional capacity and staffing for groundwater quantity data management.
- Limited public awareness and engagement in groundwater governance.
- Lack of standardized procedures for threshold values in karst aquifers.
- Incomplete integration of groundwater-dependent ecosystems (GWDE) into spatial, environmental, and water resource management planning.
- Insufficient regulation of artificial recharge and wastewater discharge in karst areas.
- Inconsistent implementation of remediation programs in sanitary protection zones, particularly in karst areas.
- Weak enforcement mechanisms for illegal waste disposal in karst areas.
- Conceptual ambiguity in defining drinking water protection areas (DWPA) under WFD.
- Limited access to raw groundwater data and interoperability across institutions.
- Groundwater abstraction data primarily collected for fee calculation, not for resource planning.
- Absence of overflow discharge measurements at major karst springs.
- Inadequate quantification of water uses in agriculture and industry, hindering groundwater budgeting.
- Limited integration of seasonal variability into groundwater management strategies
- Absence of unified national database for GWDE and GW data.

Opportunities

- Strengthening cross-sectoral coordination and participatory governance mechanisms.
- Developing environmentally grounded economic and legal instruments for karst aquifer protection.
- Enhancing public education and awareness campaigns on groundwater vulnerability.
- Integrating GWDE into national biodiversity and conservation strategies.
- Leveraging EU funding for infrastructure upgrades and wastewater treatment.
- Promoting decentralized wastewater solutions in small karst settlements.
- Implementing digital waste tracking systems (e.g. Digital Waste Shipment System, DIWASS) to prevent illegal dumping.
- Supporting sustainable tourism and agriculture through targeted incentives.
- Improving transboundary cooperation on shared aquifers and karst systems.
- Establishment of a national program for systematic overflow monitoring at karst springs.
- Development of a centralized groundwater quantity database with daily reporting obligations for all users.

- Integration of seasonal variability models into groundwater management and planning.
- Strengthening enforcement and accountability mechanisms for remediation program implementation.

Threats

- Illegal waste disposal and legacy industrial pollution in karst regions.
- Seasonal tourism pressures leading to over-abstraction and wastewater overload.
- Infrastructure deficits in rural areas affecting water supply and sanitation.
- Climate change impacts on groundwater recharge and salinization risks.
- Weak coordination between local governments and national institutions.
- Economic activities (e.g., hydropower, lithium processing) threatening GW and GWDE.
- Lack of formal environmental impact assessments for sensitive projects.
- Fragmented data exchange reducing capacity for predictive water management.
- Vulnerability of karst aquifers to rapid contamination due to geological features.
- Inadequate regulation of cumulative pressures on GW and GWDE.
- Failure to implement remediation measures increases long-term contamination risks in vulnerable karst aquifers.
- High seasonal variability in karst systems due to precipitation patterns exacerbates risks of over-abstraction and ecological degradation.
- Continued reliance on outdated or incomplete monitoring data may lead to misinformed policy decisions.

9 Gaps and opportunities

Gaps

Groundwater governance in Croatia, while institutionally and legally well-established, faces several critical gaps that hinder effective and sustainable management, particularly in karst areas. Despite alignment with EU directives and the existence of strategic documents such as the Water Act and River Basin Management Plan (RBMP), horizontal coordination across sectors – especially agriculture, tourism, and energy – remains fragmented and largely project-based. This limits the integration of groundwater protection into broader development policies.

Local-level implementation is uneven, with municipalities and utility companies in karst and rural regions often lacking technical capacity, financial resources, and trained personnel. Monitoring systems are in place but suffer from limited spatial coverage and insufficient granularity, particularly in dynamic karst aquifers where rapid infiltration and complex hydrogeology demand specialized approaches. The absence of a unified national database for groundwater-dependent ecosystems (GWDE) further impedes data-driven decision-making and environmental risk assessment.

Legal instruments do not fully account for the environmental vulnerability of karst systems. Threshold values for pollutants are not derived from site-specific environmental criteria, and there is no standardized methodology for assessing cumulative impacts on GWDE. Regulation of artificial recharge and indirect wastewater discharge into karst aquifers is underdeveloped, lacking clear technical

guidelines and impact assessment protocols. Furthermore, remediation programs in sanitary protection zones are inconsistently implemented, particularly in karst areas, and enforcement mechanisms remain weak.

Public awareness of groundwater issues is low outside expert circles, and participatory governance mechanisms are weak. Although institutions like Croatian Waters, Water Institute Josip Juraj Strossmayer and the Croatian Institute of Public Health conduct regular monitoring and reporting, these efforts are not systematically translated into public education or stakeholder engagement. The legal framework mandates transparency, but access to raw monitoring data and interoperability between institutional systems remain limited. The lack of overflow discharge measurements at major karst springs and the absence of daily abstraction reporting from all users hinder the development of accurate groundwater budgets.

Socio-economic pressures further exacerbate governance challenges. Illegal waste disposal, legacy industrial pollution, and seasonal tourism peaks pose significant risks to groundwater quality, especially in coastal karst zones. Infrastructure deficits in wastewater treatment and solid waste management persist in smaller settlements, undermining compliance with EU standards. Planned industrial and energy projects in karst areas, such as hydropower reservoirs and lithium processing facilities, lack comprehensive environmental impact assessments, raising concerns about long-term sustainability.

Vulnerability mapping and conceptual modelling are inconsistently applied, and there is no legal obligation to integrate environmental vulnerability into groundwater protection strategies. Additionally, the lack of a centralized groundwater quantity database and the limited integration of seasonal variability into groundwater planning further constrain adaptive management.

Cross-border cooperation on shared aquifers is insufficiently developed, with no binding instruments ensuring coordinated management.

In summary, while Croatia demonstrates strong institutional and legal foundations for groundwater governance, significant gaps remain in operational capacity, environmental integration, data transparency, enforcement, and stakeholder engagement.

Opportunities

Croatia presents a robust institutional and legal framework for groundwater governance, offering a solid foundation for future improvements, particularly in karst areas. One of the key opportunities lies in strengthening cross-sectoral coordination among water, agriculture, tourism, and energy sectors. Although cooperation currently occurs mainly through project-based initiatives, there is potential to institutionalize these linkages through integrated planning, formal inter-ministerial working groups, and harmonized policy instruments.

The expansion and modernization of groundwater monitoring networks, especially in karst aquifers, represent another strategic opportunity. Enhanced spatial coverage, real-time data collection, and digitalization of monitoring systems would improve early detection of pollution and support adaptive management. Establishing a national program for systematic overflow discharge monitoring at major karst springs, combined with mandatory daily abstraction reporting for all users, would significantly improve groundwater budgeting and resource planning.

The development of a unified national database for groundwater and groundwater-dependent ecosystems (GWDE), integrating spatial, ecological, and hydrological data, would facilitate data-driven decision-making and ecological risk assessments. This should be complemented by improved interoperability between institutional data systems and open access to raw monitoring data, enabling greater transparency and stakeholder participation.

Croatia's alignment with EU directives enables access to substantial funding for infrastructure upgrades, wastewater treatment, and environmental protection. Leveraging these resources can accelerate the implementation of decentralized wastewater solutions in small karst settlements, where centralized systems are often unfeasible due to terrain and population dispersion. The integration of seasonal variability models into groundwater management strategies would further enhance resilience to climate change and tourism-related pressures.

Legal and policy instruments can be further refined to incorporate environmentally grounded criteria for karst aquifer protection. This includes developing site-specific threshold values, vulnerability mapping, and standardized methodologies for assessing cumulative impacts. The integration of GWDE into biodiversity conservation strategies and Natura 2000 management plans offers a pathway to strengthen environmental safeguards.

Public awareness and participatory governance mechanisms, though currently limited, can be enhanced through targeted education campaigns, stakeholder engagement programs, and transparent communication of groundwater status. Civil society organizations and local initiatives have shown capacity to mobilize public interest, which can be harnessed to build community resilience and stewardship.

Digital innovations such as the upcoming EU-wide Digital Waste Shipment System (DIWASS) present a timely opportunity to improve waste tracking and prevent illegal dumping in sensitive karst areas. Implementing such systems at the national level would enhance regulatory enforcement and environmental accountability.

Sustainable tourism and agriculture, supported by eco-schemes under the Common Agricultural Policy (CAP), offer economic incentives for groundwater protection. High Nature Value (HNV) grassland conservation programs, particularly in karst regions, contribute to reducing agrochemical pollution and preserving groundwater quality. These programs can be expanded and better integrated into spatial and water planning frameworks.

Transboundary cooperation on shared aquifers remains underdeveloped but holds significant promise. Strengthening bilateral and regional agreements, supported by EU frameworks, can foster coordinated management of karst water resources across borders. Establishing joint monitoring programs and data-sharing protocols would enhance regional resilience.

Finally, the growing emphasis on climate adaptation and green transition in national strategies provides a policy window to mainstream groundwater resilience into broader environmental and economic planning. By aligning groundwater governance with climate goals, Croatia can ensure long-term sustainability of its most vulnerable and valuable water resources.

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