Interreg
Danube Region

Co-funded by
the European Union

LAREDAR

D.1.1.1. Scoping study on the roles of lakes and reservoirs management, defining transboundary effects

(Deliverable document)

Date: 31 March 2026

Compiled by: PP1 KÖTIVIZIG,

PP3 BOKU & PP5 UL

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Acknowledgements

Project partners and associated strategic partners contributed to the successful preparation of this report, in particular the experts of the LAREDAR project.

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Introduction

Flood events in Europe are becoming more frequent and severe due to climate change, threatening lives, property, and environmental and cultural heritage. The EU Floods Directive (2007/60/EC) highlights the importance of using retention areas to reduce flood risk. This deliverable is aligned with the EU Water Framework Directive (2000/60/EC), which requires the achievement of good ecological status and the prevention of deterioration of water bodies.

The main objective of LAREDAR project is to improve the transnational flood risk mitigation management of the Danube River Basin with elaboration of a concept of a new platform, called LAREDAR Harmonization Platform, which would enhance sustainable transnational cooperation. The platform should be based on a joint GIS database which will be integrated into the ICPDR frame and could assist the basin wide sustainable transboundary flood risk management and cooperation. According to ICPDR guiding principle on sustainable hydropower development, ensuring ecological flow regimes, fish migration, and sediment continuity are key requirements for minimizing environmental impacts of reservoirs and dams.

In the frame of Activity 1.1. Defining the relevance and roles of lakes and reservoirs in flood risk management the aim is to have a common approach and understanding of the relevance and roles of lakes and storage reservoirs in flood risk management within the Danube River Basin, in line with the EU Floods Directive (2007/60/EC).

This deliverable document's aim is to provide a comprehensive scoping study that establishes a common conceptual and methodological framework for assessing the relevance and roles of lakes and storage reservoirs in flood risk management across the Danube River Basin. The document maps existing definitions, approaches, datasets, and evaluation criteria used in the Danube countries, identifies gaps and inconsistencies, and synergies with previous EU-funded projects (LAND4FLOOD, DAREFORT, and DANUBE FLOODPLAIN) and synthesizes from scientific literature.

1. Background Information

Responsible partner: KÖTIVIZIG

Effective flood risk management in large river basins depends on the coordinated management of natural and artificial water retention systems. Lakes and reservoirs, together with natural retention systems such as floodplains, wetlands and connected groundwater bodies, play a role in regulating hydrological systems, mitigating flood peaks, ensuring water supply and sediment balance, maintaining ecological balance, and providing resilience to climate change. However, they are also recognized as significant hydromorphological pressures under the Water Framework Directive, contributing to altered flow regimes, sediment disruption, and the loss of ecological continuity. In transboundary river basins such as the Danube, their management requires a comprehensive understanding of hydrological processes, governance frameworks, and transboundary impacts.

At the European policy level, flood risk management is guided by the EU Floods Directive (Directive 2007/60/EC), which establishes a common framework for assessing and managing flood risks across Member States. The Directive requires countries to carry out preliminary flood risk assessments, develop flood hazard and risk maps, and prepare Flood Risk Management Plans (FRMPs) for river basin districts. A core principle of the Directive is the coordination of measures within international river basins, ensuring that flood risk management actions implemented in one country do not adversely affect others, while strengthening transboundary cooperation and supporting ecological continuity, sediment transport, and hydromorphological conditions across borders.

In the Danube River Basin, the implementation of the Floods Directive is coordinated through the International Commission for the Protection of the Danube River (ICPDR). Within the ICPDR framework, the Flood Protection Expert Group (FP EG) facilitates cooperation among Danube countries in the development and updating of basin-wide flood risk management strategies. The group promotes harmonized methodologies, information exchange, and coordinated planning in order to enhance flood protection and resilience across national borders, including the integration of ecological considerations such as river continuity, sediment dynamics, and ecosystem resilience.

Furthermore, flood risk management is closely linked with the EU Strategy for the Danube Region (EUSDR), particularly Priority Area 5 (PA5) – Environmental Risks, which focuses on improving preparedness and response to floods, droughts, and other climate-related hazards. PA5 supports cooperation among countries and institutions to strengthen monitoring systems, improve risk assessment, and promote integrated water management approaches, including nature-based solutions and the restoration of natural retention capacity throughout the Danube macro-region. The LAREDAR project contributes to these objectives by enhancing knowledge on retention systems and supporting improved coordination in the management of lakes and reservoirs for flood mitigation and risk management..

The Danube River Basin represents one of the largest and most complex transboundary river systems in Europe. Extending from the Black Forest in Germany to the Black Sea, the basin integrates diverse climatic zones, geomorphological structures, and hydrological regimes. This report provides a comprehensive description of the Upper, Middle, and Lower Danube regions together with their major tributaries and smaller river systems. Particular attention is given to the hydrological characteristics of the basin, the interaction of tributaries, flood dynamics, and the role of lakes and reservoirs in regulating water flows. The basin includes numerous major tributaries such as the Inn, Drava, Sava, Tisza, and Morava rivers, each contributing to the complexity of the overall hydrological network. The report also discusses the influence of mountainous regions including the Alps, Carpathians, and Dinaric ranges, which strongly control runoff generation and seasonal discharge patterns. Hydrological extremes, including floods and droughts, are increasingly important challenges for water management across the basin. In addition to natural hydrological processes, extensive human modifications such as dams, reservoirs, levees, and canal systems have significantly altered river dynamics, leading to hydromorphological pressures and reduced ecological connectivity, as recognized under the Water Framework Directive. Integrated basin management and international cooperation remain essential for sustainable water resource management across the Danube basin.

Historically, the Danube River Basin has experienced several major flood events that have significantly influenced flood management policies and infrastructure development across the region. Among the most notable events are the 2002 Central European floods, which affected large parts of the Upper Danube and its tributaries, causing widespread damage in Germany, Austria, and the Czech Republic. Another major event occurred in 2006, when prolonged snowmelt combined with heavy rainfall generated extensive flooding along the Middle and Lower Danube, affecting countries including Hungary, Serbia, Romania, and Bulgaria. The 2010 floods, particularly severe in the Sava and Tisza sub-basins, caused substantial economic losses and highlighted the vulnerability of several tributary systems. More recently, the 2013 Danube floods represented one of the most significant flood events in recorded history in parts of the basin, with extremely high discharge levels observed along the Upper and Middle Danube and major impacts in Germany, Austria, Slovakia, and Hungary. These events demonstrated the transboundary nature of flood risks, highlighted the importance of restoring natural retention areas, and the importance of coordinated basin-wide flood risk management, improved forecasting systems, and the strategic use of retention areas, including reservoirs and natural floodplains.

Roles of Lakes and Reservoirs in Flood Management and Transboundary Context

Lakes and reservoirs function as key components of integrated water management systems alongside natural retention systems such as floodplains and wetlands. Natural lakes contribute to flood attenuation by temporarily storing part of the water volume and delaying the flood peak during high-flow events, while reservoirs—through controlled operation—can reduce downstream flood peaks, although such regulation may also modify natural flow regimes and sediment transport processes. Their effectiveness depends on operational rules, storage capacity, catchment characteristics, and coordination with other flood mitigation measures such as floodplains, wetlands, and levee systems.

In transboundary river basins, the operation of reservoirs or the management of large lakes in one country may directly affect downstream hydrological conditions including impacts on ecological status and river continuity in neighboring states. These transboundary effects include changes in flood peak timing, discharge volumes, sediment transport, water quality, and ecological conditions. Particular attention should be given to impacts on sediment balance, habitat conditions, and connectivity of aquatic species across borders. Therefore, coordinated reservoir operation, shared hydrological data, and harmonized management approaches are essential to prevent negative downstream impacts and to maximize basin-wide flood protection benefits, while ensuring compliance with the Water Framework Directive, particularly the non-deterioration principle.

In strengthening its methodological foundation, Activity 1.1 will actively build on knowledge generated by previous EU-funded initiatives. LAND4FLOOD focused on the role of privately owned land in providing space for flood retention and highlighted the importance of integrating natural retention measures into broader flood risk management strategies. Its findings on governance, stakeholder engagement, and land-use challenges provide valuable insights for understanding how lakes and reservoirs can complement natural retention solutions. DAREFORT contributed to improving real-time data exchange, forecasting, and transboundary cooperation across the Danube River Basin. Its outcomes support Activity 1.1 by demonstrating how harmonized information and coordinated management can enhance decision-making for flood control structures, including reservoirs. DANUBE FLOODPLAIN concentrated on identifying, assessing, and restoring active and potential floodplains, emphasizing nature-based solutions and their role in reducing flood peaks using the **Floodplain Evaluation Matrix** (FEM), while also supporting ecosystem resilience and biodiversity. The current activity has strong coherence with this work, as both projects seek to optimize natural and artificial retention areas and to understand their combined benefits for flood risk reduction.

By aligning with these earlier initiatives, Activity 1.1 ensures continuity, avoids duplication, and contributes to a shared, basin-wide perspective on using lakes, reservoirs, and floodplains as interconnected elements of resilient flood management, fully consistent with the objectives of the EU Floods Directive, the coordination framework of the ICPDR Flood Protection Expert Group, and the strategic priorities of EUSDR PA5.

2. Basic definitions of lake and reservoir management

The LP KÖTIVIZIG elaborated the Catalogue of basic definitions of lake and reservoir management with project partners as input for **D1.1.1 Scoping study on the roles of lakes and reservoirs, defining transboundary effects.** Different interpretations of the same terms across partners can lead to miscommunications, so the main aim is to ensure a common understanding of key terms used throughout the LAREDAR project. A shared understanding of key terms is the foundation of effective collaboration. The project involves diverse teams with varying backgrounds. A catalogue of basic definitions standardizes definitions upfront, reducing errors. This document serves as a central reference, defining essential terms and water management-specific language in simple, precise, nontechnical ways that convey basic meanings.

2.1. Key Benefits

- Minimizes misunderstandings, enabling all partners to operate with consistent definitions and improving task execution. This will protect project scope creep.
- Facilitates effective communication of complex, profession-related concepts among partners, as well as with external stakeholders, the public, and supporters. This will enhance knowledge sharing. This bridges expertise gaps, empowering non-experts to contribute meaningfully.
- Supports clear on boarding for new members, preventing scenarios where terms are understood differently.
- Ensures internally produced deliverables and those from external sources align with project requirements and scope management.
- Aids readers of project publications by providing building blocks of the project's language.
- Clear, unambiguous definitions of fundamental terms and principles are essential for these outcomes, forming the basis for continuous project implementation.

2.2. Development Process and Sources

The catalogue gathers terms and definitions from all partners in one location, focusing on the most frequent and important ones. Sources for definitions include the Water Framework Directive (WFD), Floods Directive (FD), EU Directives, and Infrastructure for Spatial Information in the European Community (INSPIRE), International Commission on Large Dams (ICOLD), Water laws from various countries and Water Acts. The scope involved identifying terms, disseminating them for partner feedback, compiling responses, and deriving common definitions.

Understanding these sources highlights the terms' critical role in the project. The result: a vocabulary that supports conceptual understanding, linguistic communication, and easy learning.

2.3. Ongoing Role

Key phrases may evolve as the project progresses and implementation needs arise, adapting to the working language. This creates a project environment where everyone "speaks the same language," enhancing overall efficiency.

2.4. Catalogue of basic definitions

Term	Common definition
(unregulated) lake	A standing inland body of water, of natural or artificial origin surrounded by land and not part of the ocean with or without inflow and outflow through rivers or streams.
active reservoir capacity	Useful volume of storage reservoir allocated for different purposes provided.
coordination in case of flood with the upper and the downstream reservoirs	Operators coordinate upstream, midstream, and downstream releases to: optimize water storage and release, minimize flood risk, and protect communities and infrastructure along the river.
daily fluctuation in water levels (permissible)	Daily water level fluctuations (permissible) in reservoirs are natural or regulated changes in the height of the water table during the day
dam	A dam is a barrier that impounds water or underground streams.
damming effect on the river section	The changes in the physical, hydrological, and ecological characteristics of a river upstream and downstream caused by the construction and operation of a dam.
design flood	The design flood is the maximum flood flow (or flood volume) that a dam, reservoir, spillway, or flood control system is designed to safely handle without failure or unacceptable risk.
ecological flow	Ecological flow (environmental flow regime) refers to the quantity, timing, variability, and seasonal dynamics of flows required to sustain aquatic ecosystems, sediment transport processes, and ecological continuity.
river connectivity	The degree to which a river system is connected longitudinally (upstream–downstream), laterally (river–floodplain), and vertically (surface water–groundwater),

	enabling the natural movement of water, sediments, nutrients, and aquatic organisms, and supporting the ecological integrity and functioning of the river ecosystem.
flash flood	A flash flood is a sudden, short-term rise and fall quite rapidly (minutes or few hours) with little or no advance warning in water level in a river that occurs irregularly and is caused by heavy rains, rapid melting of snow during thaws, or water releases from reservoirs.
flood	Flood is the temporary covering by water of land not normally covered by water.
flood control storage	The flood protection volume is the volume of a reservoir (or polder) designed to accumulate flood runoff in order to reduce the risk of flooding (flood mitigation).
flood risk	Flood risk is a combination of the probability of flooding and its potential negative impacts
inactive storage	The inactive storage is the volume of water below the lowest inlet elevation, unusable for different purposes provided by the storage. The part of the reservoir volume which under normal operating conditions is not used to regulate flow
maximum discharge	The maximum discharge is the highest flow rate of water that a reservoir, dam, or spillway is designed or allowed to release downstream safely. Historical maximum discharge: the highest flow ever measured at a specific river section. Design maximum discharge: the calculated flow used for designing hydraulic structures (e.g. spillways, bridges, levees) to ensure safety during extreme flood events.
mean annual inflow (into the reservoir)	Mean annual inflow – is the average year value of water inflow to the reservoir per year
minimum considerable size	Minimum considerable size of a reservoir can vary depending on context (e.g., legal, engineering, or environmental), but it generally refers to the smallest size at which a reservoir is considered significant enough to be regulated, monitored, or included in planning and policy.
minimum considerable volume	The minimum operating volume of a water reservoir is the minimum amount of water that must be in the reservoir to perform its functions. The minimum considerable volume of a reservoir refers to the smallest storage capacity at which a reservoir is regarded as significant enough to be

	subject to regulation, safety standards, reporting, or inclusion in water management planning.
minimum discharge	Is the lowest flow of water released or allowed to flow downstream from a reservoir or dam that still ensures the operating water level of the reservoir. Is the minimum discharge required to be permanently released downstream of a dam or water intake, consisting of the ecological flow and the minimum flow required for downstream users
minimum size of catchment	The smallest area of land draining water into a reservoir, river, or other water body that is deemed worth monitoring or managing. The minimum catchment area of a water reservoir is not strictly defined by a single number, but depends on several factors, such as hydrological, morphological and topological conditions
operating authority	A dam operating authority is the entity responsible for the safe operation, maintenance, and surveillance of a dam. This authority can be a government agency, a private company, or a combination of both, and their responsibilities include ensuring the dam functions as intended, minimizing risks to life and property, and complying with all relevant regulations.
operating regulations	The official technical document that establishes in detail the set of rules, conditions, procedures, technical and organizational measures necessary for the safe and efficient operation of the dam and its associated storage reservoir
polder	Polder is an embanked, hydraulically controlled, temporary storage area designed for regulated flood peak reduction. It is filled only when the river passes the maximum flow in order to reduce the water level in the river
purpose of the reservoir	A reservoir in which water is retained so that it can be used for some purposes including urban and local water supply, irrigation, recreation, flood control, wild life habitat, and transportation/navigation etc.
regulated/unregulated reservoir (by outflow)	**Regulated** Reservoir is a reservoir where the outflow is controlled by man-made structures (gates/weirs) to manage both high and low flows.

	Unregulated Reservoir is a reservoir where the outflow is not actively controlled - it flows naturally, typically via an overflow spillway. The outflow depends on the upstream water flow and the size of the culvert.
reservoir	Bodies of water that are usually artificially impounded by the construction of dams
retention basin	Surface or underground reservoirs designed to modify the flood waves of runoff resulting from precipitation, discharging only via controlled outlets.
role in case of flood	The role is primarily to eliminate the damage caused by floods by regulating the flood wave in time by: Temporarily store excess water, dampen and delay flood peaks, enable controlled release after the event subsides
role in case of water scarcity	In case of water scarcity the reservoir plays the role of: Maintaining ecological flows and aquatic habitat via sustained base flows. Recharging groundwater, providing water storage for supplementary irrigation, municipal use, recreation, animal supply, electricity production
storage capacity	Storage capacity is the maximum volume of water that can be stored within a lake, reservoir, or regulated water body. The sum of the active and inactive capacity.
transboundary effect	Lakes and reservoirs located on transboundary rivers that have a significant impact on the natural water regime: Lakes and reservoirs located on transboundary rivers within the Danube River Basin, particularly those associated with river catchments of basin-wide relevance. Systems with a potential or demonstrated influence on the transboundary water regime, such as effects on flood wave propagation, backwater effects, or retention and attenuation processes.
(unregulated) lake	A standing inland body of water, of natural or artificial origin surrounded by land and not part of the ocean with or without inflow and outflow through rivers or streams.
weir/dam type	A weir is a type of hydraulic structure used to control or measure the flow of water in open channels, rivers, or spillways. The weir type refers to the specific design or shape of the weir such as rectangular, triangular (V-notch), and trapezoidal, which affects how water flows over it and how flow is measured or controlled.

3. Challenges related to hydrological extremes on the Danube River Basin

The Danube River Basin (DRB) is one of Europe's most hydrologically diverse and operationally complex river systems. Extending from Alpine headwaters through major lowland plains to the Danube Delta and the Black Sea, it integrates a wide range of hydro-climatic, geomorphological, and socio-economic settings. Hydrological extremes in the basin are therefore not isolated local events, but interconnected processes shaped by topography, river regulation, climate variability, land use change, and strong transboundary interdependence.

Across the basin, floods are generally associated with several recurring mechanisms: prolonged large-scale rainfall, Vb-type Mediterranean cyclones, rain-on-snow events, rapid snowmelt, and the synchronization of flood waves from major tributaries. Droughts and low-flow periods represent a parallel and increasingly severe challenge. These events are intensified by summer heatwaves, changes in seasonal runoff, reduced natural water retention capacity, and growing water demand, directly affect navigation, hydropower generation, agriculture, ecosystems, and drinking water supply. Because the Danube is shared by many countries, the timing and severity of these extremes are strongly influenced by upstream processes, including reservoir operation, retention management, forecasting quality, and land and water management decisions. This makes transboundary coordination a core requirement for effective risk reduction and for maintaining ecological status across the basin.

From a scoping perspective, the DRB can be interpreted as a sequence of hydrological regions with distinct but connected extreme-event profiles. The Upper Danube is dominated by steep Alpine and sub-Alpine tributaries and rapid flood responses. The Middle Danube is characterized by lowland hydrology, influenced by the upstream mountainous regions (the Carpathians, the Balkans, and the Alpine area) long flood durations, major floodplain transformations, and strong dependency on upstream inflows. The Lower Danube adds low gradients, backwater effects, large-scale sediment dynamics, and deltaic processes, while also concentrating multiple transboundary risk interfaces. Taken together, these features confirm that hydrological extremes in the Danube Basin must be managed through integrated, basin-scale, multi-hazard strategies rather than national or sectoral approaches alone.

3.1. Upper Danube Region

The Upper Danube Region, covering Germany, Austria, and Slovakia, is characterized by high hydrological connectivity, rapid runoff generation in mountainous tributaries, and strong control of flood severity by upstream conditions. Floods in this region are often generated and influenced by upstream retention and regulation measures in Alpine or sub-Alpine catchments and are then transmitted downstream through the Danube corridor. Consequently, extreme water levels are shaped not only by local rainfall, but by the timing, volume, and superposition of tributary waves. At the same time, drought and low-flow conditions increasingly affect navigation, ecological status, energy production, and overall water-resource reliability.

3.1.1. Germany

In the German Danube, hydrological extremes are strongly driven by tributary systems rather than by the main stem alone. The Bavarian Danube primarily functions as a receiving and conveying corridor, while major tributaries such as the Iller, Lech, Isar, and especially the Inn determine the magnitude and structure of major flood events. This creates a pronounced upstream–downstream dependency in which flood severity at any given point is controlled by the distribution of rainfall across sub-basins, antecedent catchment wetness, snow storage conditions, and the coincidence of flood peaks at confluences such as Passau.

A defining hydrological feature of the German Danube is the contrast between fast-responding tributaries and the slower-reacting Danube main stem. Steep tributary basins can produce intense flow surges over short periods, whereas the Danube often remains at elevated levels for longer durations. This mismatch promotes wave superposition, which is a recurrent cause of severe flooding in downstream reaches. The June 2013 flood is a key example: prolonged multi-day rainfall, saturated soils, and the synchronization of tributary inflows generated exceptionally high downstream water levels and remains a central reference event in German flood-risk assessment.

Flood management in Germany is structured around hazard and risk planning standards such as HQ100, in line with the requirements of the EU Floods Directive. However, the concept of overload situations remains particularly important. When events exceed the design envelope, overtopping, structural damage, and cascading failures become more likely, affecting settlements, ecosystems, transport infrastructure, utility systems, and pollution-sensitive installations. In parallel, low-flow periods create another critical risk dimension, since the Danube functions not only as a river but as a federal waterway and strategic logistics axis. During drought years such as 2018, persistent low water levels significantly constrained navigation and added ecological stress, demonstrating that in the Upper Danube context both flood and drought management must be treated as core components of the same resilience framework, integrating both technical and nature-based measures. The 2022 European drought further reinforced this concern, as prolonged low water levels across the Danube system severely impacted navigation, hydropower generation, and water supply throughout the basin.

Historically, Germany's Upper Danube has experienced several benchmark events that continue to shape planning and modelling. The 1954 flood demonstrated downstream accumulation under widespread rainfall; the 1999 "Pfingsthochwasser" highlighted the combined influence of long-duration precipitation, wet antecedent conditions, and snowmelt; the 2002 and 2005 events illustrated strong tributary interaction and orographic control; and the 2013 event became the defining contemporary example of tributary synchronization. These cases underline that flood hazard in the German Danube is highly corridor-based and cannot be understood through local hydrology alone.

Within the German Danube basin, two reservoirs meet the LAREDAR minimum inclusion thresholds for flood risk relevance. The Forggensee on the river Lech (basin area 1,585.8 km^2, total storage capacity 168 Mio m^3, flood control storage 22 Mio m^3) serves primarily for hydropower generation with secondary flood control functions, operated by Uniper Kraftwerke GmbH. The Sylvensteinspeicher on the river Isar (basin area 1,138 km^2, total storage capacity 124.3 Mio m^3, flood control storage 60.7 Mio m^3) is a publicly owned flood control and hydropower reservoir operated by the Wasserwirtschaftsamt Weilheim. Both reservoirs are located in the Alpine foreland of Bavaria and influence downstream discharge patterns, hydrological regimes, and sediment dynamics toward the Austrian border. It should be noted that Germany has no designated LAREDAR pilot area; however, the German Danube model results can be integrated into the LAREDAR GIS platform for visualization and analysis. TUM (PP2) is currently transitioning the German Danube hydraulic model from SOBEK to HEC-RAS to improve compatibility with partner models across the Danube region.

3.1.2. Austria

Austria occupies a pivotal position within the Danube Basin, linking the Upper Danube to the middle and lower sections toward Slovakia and Hungary. About 96% of Austrian territory drains into the Danube system, including major tributaries such as the Inn, Salzach, Enns, Traun, Mur/Mura, Drau/Drava, and March/Morava. Austrian hydrology is predominantly Alpine, with nival and glacial influences in mountain areas and more pluvial behaviour in the foreland and Pannonian zones.

Flood generation in Austria is governed by several hydro-climatic processes that often interact and areinfluenced by catchment conditions and upstream processes. Late spring and early summer are the most critical periods, when snowmelt coincides with prolonged rainfall and produces broad, long-duration floods. Summer contributes convective storms and local flash-flood peaks, while autumn floods are often linked to extended rainfall on already wet catchments. Winter rain-on-snow events can also trigger rapid runoff. A characteristic feature of Austrian Danube floods is their multi-peaked hydrograph structure, reflecting the fact that tributaries crest at different times and that travel times between locations such as Passau and Vienna influence downstream wave interaction. While hydropower structures and reservoirs may attenuate floods locally and modify flow regimes, they do not fundamentally eliminate large flood volumes at the basin scale.

Austria has a long history of flood defence and river regulation, at first along the Danube in Vienna. Since the late eighteenth century, flood management evolved from local dikes and levees toward channel recalibration, structural reinforcement, and modern hazard-based planning. Today, Austrian flood management operates within the framework of hazard and risk maps for HQ30, HQ100, and HQ300 events, combined with Flood Risk Management Plans under the EU Floods Directive. Equally important is the conceptual transition from traditional flood defence toward integrated flood risk management. This shift recognizes that effective management must combine structural protection with spatial planning, ecological considerations, retention functions, and intersectoral coordination.

Austria's reservoir and hydropower systems play a major role in national water management, but their flood-control influence varies by location. Large storage reservoirs are concentrated in the Alpine headwaters and can contribute to attenuation in upper basin sections, while numerous run-of-river structures along the Danube, Inn, Drava, and Mura have more limited basin-scale flood-mitigation capacity. Historical flood records in Vienna including 1501, 1787, 1899, 1954, 2002, 2013, and 2024 demonstrate that major events are a structural feature of the Austrian Danube.

Within Austria, the Mura basin is particularly relevant from a scoping perspective. It links Alpine source areas with Slovenia and further downstream Danube tributary systems, and combines several critical features: strong orographic rainfall control, a pluvio-nival regime, run-off hydropower development, embankment-reinduced natural retention capacity with floodplain loss, and rising agricultural and urban exposure. Although hydropower structures are numerous, most have relatively limited retention volumes, which constrains their flood-reduction potential. By contrast, remaining natural floodplain areas along the Austrian–Slovenian border still have ecological importance and may still have substantial retention value, though this requires further quantification. Recent flood events in 2005, 2012, 2014, 2023, and 2024, together with increasing evidence of drought and dry-spell risk, indicate that the Mura is a dynamic transboundary sub-basin whose future management will be affected by climate change.

3.1.3. Slovakia

Almost the entire territory of Slovakia lies within the Danube Basin, making the country highly dependent on hydrological processes both within and beyond its borders. Flood and drought management in Slovakia is therefore inseparable from upstream conditions, reservoir operations, and cross-border hydrological connectivity. A defining characteristic of Slovakia is the concentration of large storage capacities in upper and middle basin sections, especially in mountainous and sub-mountainous areas. This gives the country considerable potential for source-area flood attenuation, because runoff generated in zones of high precipitation and snow accumulation can be intercepted before propagating downstream.

In contrast, lower-basin structures such as flow-through reservoirs on the lower Váh and Danube are oriented more toward hydropower, navigation, and short-term regulation than toward long-term storage of large flood waves. This spatial differentiation in storage function is highly relevant from a Danube-basin perspective, as it shows how flood-management effectiveness depends not only on the number of hydraulic structures but on their position within the basin and their active storage capacity.

Reservoir operation in Slovakia is institutionally formalized and supported by a clear administrative structure. The Slovak Water Management Company manages most watercourses and reservoirs, while Vodohospodárska výstavba is responsible for major strategic systems such as Gabčíkovo. Oversight by the Ministry of the Environment and technical-safety supervision provide an additional governance layer. In this framework, hydrometeorological data supplied by the Slovak Hydrometeorological Institute are essential for operational decisions.

A particularly important development is the integration of forecasting and reservoir control through the POVAPSYS system. By combining real-time monitoring, meteorological forecasts, and hydrological modelling, POVAPSYS supports preventive releases, temporary storage creation, and coordinated operation across cascades such as the Váh. This represents a shift from reactive toward anticipatory reservoir management and provides a strong example of how forecasting can enhance transboundary flood-risk reduction. Slovakia's technical registries, GIS databases, and INSPIRE-compliant spatial datasets also contribute to a robust planning environment and are directly relevant for LAREDAR-type risk analyses.

The chapter also highlights the hydrological importance of the Morava and Dyje systems for Slovakia and the lower Danube corridor. The fan-shaped tributary geometry of the Morava basin creates a strong risk of flood-wave superposition during widespread rainfall. In the Dyje basin, the September 2024 event demonstrated how coordinated reservoir operation - particularly at Vranov and Nové Mlýny - can substantially reduce downstream peaks and prevent critical coincidence with the Danube near Bratislava. This case illustrates the broader principle that flood risk in the Upper Danube cannot be understood in national isolation: forecasting, retention, and transboundary operational coordination are central to basin-wide resilience.

3.1.4 Czech Republic

Although only a relatively small proportion of the Czech Republic lies within the Danube River Basin, the country plays a strategically important role in the hydrological functioning of the Upper Danube through its contribution to the Morava and Dyje (Thaya) river systems. These rivers form key transboundary tributaries connecting Czech territory with Austria and Slovakia before ultimately joining the Danube. As a result, hydrological processes occurring in the Czech Republic can have significant downstream implications, particularly during extreme flood events.

The hydrological regime of the Czech Danube sub-basins is influenced by a combination of mountainous and upland catchments, relatively dense river networks, and strong seasonal variability in precipitation. Flood generation is typically associated with prolonged frontal rainfall, convective summer storms, rapid snowmelt, and rain-on-snow events. The country's location at the intersection of Atlantic, continental, and Mediterranean climatic influences contributes to considerable variability in hydrological conditions from year to year.

The Czech Republic has experienced several major flood events that have significantly shaped national water management policies. The catastrophic floods of 1997 in the Morava basin and the widespread Central European floods of 2002 remain benchmark events in the country's flood-risk history. The 1997 floods caused extensive damage across eastern Czechia and demonstrated the vulnerability of settlements located in narrow valleys and floodplains. The 2002 floods, driven by prolonged and intense rainfall, affected large parts of the country and reinforced the importance of integrated basin-scale flood management. More recent events, including floods in 2010, 2013, and 2024, have further highlighted the need for continuous adaptation of flood protection systems under changing climatic conditions.

A distinguishing feature of the Czech water-management system is the extensive network of multipurpose reservoirs and reservoir cascades. Major reservoirs such as Vranov, Vír, Nové Mlýny, and numerous structures within the Vltava and Morava basins provide significant capacity for flood attenuation, water supply, hydropower generation, and drought mitigation. From the perspective of the Danube Basin, the Dyje reservoir system is particularly important because coordinated reservoir operation can substantially influence downstream flood-wave propagation toward Austria and Slovakia. Recent operational experiences have demonstrated that forecast-based reservoir management can effectively reduce peak discharges and delay flood-wave coincidence at critical downstream confluences.

At the same time, the Czech Republic is increasingly exposed to drought and low-flow conditions. Since the early 2000s, several prolonged drought periods have affected agriculture, water supply systems, ecosystems, and hydropower production. Severe drought episodes between 2015 and 2020 highlighted the growing importance of integrated flood and drought management, where reservoirs must simultaneously provide flood protection capacity and secure strategic water reserves during dry periods.

Climate-change projections indicate rising temperatures, increasing precipitation variability, more frequent short-duration extreme rainfall events, and reduced snow accumulation in mountain regions. These trends are expected to alter runoff seasonality, increase flash-flood risk in smaller catchments, and intensify drought occurrence. Consequently, adaptive reservoir operation, improved forecasting systems, enhanced retention measures, and strengthened transboundary cooperation with Austria and Slovakia are expected to become increasingly important elements of Czech water management within the wider Danube River Basin context.

3.2. Middle Danube Region

The Middle Danube Region, including Hungary and Serbia and closely linked with Slovenia, represents the transition from Alpine-influenced hydrology to predominantly lowland river systems. In this region, flat topography, long flood-wave durations, extensive sedimentation, transformed floodplains and reduced natural retention capacity become the dominant controls on hydrological extremes. Floods are often slower than in the Upper Danube, but more extensive and persistent. At the same time, particularly under changing climatic conditions, water scarcity becomes increasingly significant because agricultural demand is high, natural gradients are low, and drainage and retention systems are heavily engineered.

3.2.1. Hungary

Hungary occupies a unique and highly exposed position within the Danube Basin. Located entirely within the Carpathian Basin, it receives approximately 96% of its surface water from upstream countries. This makes Hungary one of the most transboundary-dependent water-management systems in Europe. Around 23% of the national territory is protected by flood-defence infrastructure, and roughly one quarter of the population lives in flood-prone areas.

Because of the country's flat terrain, flood waves propagate slowly, remain in the system for long periods, and can cause widespread inundation. Flood management has therefore been a defining component of Hungarian state formation and landscape and water management development for centuries. The country has built an extensive system of embankments, reservoirs, pumping stations, and associated hydraulic works, with more than 4,200 km of levees supporting protection generally oriented toward 100-year events.

One of the most distinctive features of Hungarian water management is its historically integrated character. Long before current European policy frameworks, Hungary had already developed a practice of addressing flood protection, drainage, irrigation, and water use in a coordinated way. This is particularly important because Hungary must manage not only river floods but also "inland water," a characteristic hazard of lowland basins where water accumulates on flat terrain due to high groundwater, limited drainage, and heavy precipitation. Inland water affects very large areas and illustrates that in low-gradient landscapes, excess water and water shortage can coexist as parallel management problems.

Flood regimes on the Hungarian Danube are dominated by late winter–early spring events linked to snowmelt and rainfall, and by summer floods originating from intense Alpine precipitation. Ice floods historically played a major role, although their relevance has decreased. Major events in 2002, 2006, and especially 2013 produced record water levels and reinforced awareness that long flood durations and high stages place exceptional pressure on protection systems.

Hungary's flood-risk management history is closely linked to the transformation of the Tisza. Nineteenth-century regulation works radically altered the landscape, reduced natural floodplain storage, and enabled economic development across the Great Plain. At the same time, this transformation increased dependence on artificial protection and reduced natural floodplain retention while contributing to higher flood levels and longer persistence of flood waves over time. Since the late twentieth century, observations have shown that sedimentation, vegetation encroachment, and reduced conveyance have amplified these tendencies over time.

The sequence of extreme Tisza floods between 1998 and 2010 triggered a major policy shift. The further development of the Vásárhelyi Plan introduced a more integrated flood-risk management approach, combining structural and non-structural (nature-based) measures and emphasizing controlled flood retention. The creation of a system of flood-peak reduction reservoirs, with total storage exceeding 1 billion m^3, reflects a strategic move away from reliance on levees alone.

At the same time, Hungary has increasingly recognized drought and low-flow risk as an equally important challenge. Water transfer systems such as TIKEVIR, and infrastructure such as the Kisköre Barrage and Lake Tisza, support irrigation, ecological water supply, and retention in water-deficient regions. This demonstrates that in the Middle Danube context, the same hydraulic system must simultaneously address flood protection, drought mitigation, ecological support, and water redistribution. The country's large lakes-Balaton, Fertő, and Velence-further underline the importance of climate-sensitive water bodies in regional hydrology, ecosystem functioning,, and tourism.

3.2.2. Slovenia

Although geographically smaller, Slovenia is highly relevant within the Middle Danube context because it represents a dynamic hydrological transition between Alpine and lowland environments. About 81% of its territory lies in the Danube Basin, primarily within the Sava, Drava, and Mura systems. Its topographic diversity, together with karst formations and steep valley systems, produces rapid hydrological responses and a high susceptibility to flash floods.

Flood risk in Slovenia is concentrated in valleys and basins where settlement, infrastructure, hydropower, and agriculture are also concentrated. This creates strong exposure across multiple sectors. Groundwater-dependent drinking water systems and ecologically sensitive lakes further increase the complexity of hydrological risk. At the same time, hydropower is highly exposed to both flood inflows and drought-related flow deficits, reflecting the dual nature of water extremes in the country.

Recent experience demonstrates growing vulnerability. The August 2023 floods were the most severe natural disaster in Slovenia's recent history, affecting two-thirds of the country and causing extensive damage to settlements, infrastructure, and ecosystems. Earlier events in 1990, 1998, 2004, and 2010 show that severe floods are recurrent and linked to intense rainfall and rapid catchment response. Droughts in 2003, 2012, and 2022 confirm the other side of the hydrological extreme spectrum, with prolonged precipitation deficits, reduced river flows, and impacts on water resources and ecosystems.

From a scoping perspective, Slovenia illustrates how rapidly responding tributary systems, karst hydrology, and strong sectoral exposure can amplify both flood and drought risk. Future climate trends point to rising temperatures, more variable precipitation, and increasing event intensity, making adaptive water and reservoir management increasingly necessary.

3.2.3. Serbia

Serbia represents the downstream part of the Middle Danube Region and combines lowland hydrology with transitional mountain-fed tributary systems. Around 92.6% of its territory lies within the Danube Basin, and more than 90% of renewable water resources originate outside the country, underscoring its dependence on transboundary inflows.

Northern Serbia, particularly the Tisza basin in Vojvodina, is characterized by flat terrain, intensive agriculture, and highly managed water systems. The Danube–Tisza–Danube canal network plays a central role in drainage, irrigation, and water-level control and is a key example of multifunctional lowland water management. Flood regimes are typically rain–snow driven, with spring maxima and summer low flows, but Serbia is exposed to a wide range of flood types including pluvial floods, snowmelt floods, coincident flood waves, flash floods, and historically important ice floods.

Major historical events, especially 1965, 2006, and 2014, illustrate the scale of Serbia's flood vulnerability. The 1965 flood affected all major river systems and caused extensive levee failures and widespread damages, while the 2006 and 2014 events demonstrated that basin-wide and multi-basin flooding remains a serious contemporary risk. In Serbia, flood protection has expanded significantly over time through embankment construction, river regulation, and hydraulic infrastructure, but flood duration, upstream dependency, and transboundary inflow conditions remain central constraints.

Reservoir systems such as Novi Bečej on the Tisza provide irrigation, navigation, and water-supply benefits, but they have relatively limited flood-mitigation capacity compared to larger source-area storage systems in upstream countries. Serbia’s hydrological landscape also includes oxbows, shallow lakes, and smaller reservoirs, which are relevant for local water management and ecology but do not fundamentally alter the flood regime of the main rivers.

Drought has become increasingly significant since the early 2000s. Major droughts in 2000, 2003, 2007, 2012, 2017, and 2022 caused serious agricultural losses and also affected power generation, water supply, and navigation. The severe summer drought of 2024 further underlined the growing role of climate change in shaping Serbian water risks. With increasing temperatures, changing precipitation patterns, and more frequent extremes, Serbia faces the challenge of modernizing its monitoring, forecasting, and integrated water management while strengthening its role in transboundary Danube and Tisza cooperation.

3.2.4. Croatia

Croatia occupies a strategically important position within the Middle Danube Region, where several major transboundary river systems converge. Approximately two-thirds of the country's territory belongs to the Danube River Basin, primarily through the Drava, Sava, and Danube, Mura, and Kupa river systems. As both an upstream and downstream stakeholder within different sub-basins, Croatia is strongly influenced by hydrological processes originating in neighbouring countries while simultaneously affecting downstream flood conditions in Serbia and Hungary.

The Croatian section of the Danube Basin is characterized by diverse hydrological conditions. Mountainous and hilly catchments in the northwest generate relatively rapid runoff responses, while the extensive lowland floodplains along the Sava, Drava, and Danube rivers are dominated by slower flood-wave propagation, significant floodplain storage, and strong river–floodplain interactions. These contrasting hydrological environments create a wide range of flood mechanisms, including riverine floods, flash floods, snowmelt-related events, and combined rainfall-runoff processes.

Flood risk in Croatia is particularly associated with the Sava River system, one of the largest tributaries of the Danube. The Sava basin integrates hydrological inputs from Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, and Serbia, making flood management inherently transboundary. Major flood events often result from prolonged regional rainfall affecting large portions of the basin simultaneously. Under such conditions, synchronization of tributary inflows can generate extensive flooding along the main river corridor.

Several significant flood events have influenced Croatian water-management policies. The floods of 1964, 1998, 2010, and particularly the widespread floods of 2014 demonstrated the vulnerability of settlements, agricultural land, and infrastructure throughout the Sava basin. The 2014 event, associated with exceptional rainfall across large parts of Southeast Europe, caused extensive flooding in Croatia and neighbouring countries and reinforced the importance of coordinated basin-wide forecasting and emergency management. More recent flood episodes have highlighted the increasing frequency of hydrological extremes under changing climatic conditions.

Croatia possesses a substantial network of flood-protection infrastructure, including levees, flood-retention areas, polders, drainage systems, and hydraulic structures managed by Hrvatske vode. One of the most distinctive features of Croatian flood management is the continued importance of large natural and semi-natural flood-retention areas, particularly within the central Sava basin. Systems such as Lonjsko Polje represent internationally significant floodplain complexes that provide substantial temporary storage during high-flow events. These areas contribute not only to flood mitigation but also to biodiversity conservation, groundwater recharge, and ecosystem resilience.

Reservoirs play a more limited role in Croatian flood management compared with countries possessing extensive mountain storage systems. Nevertheless, hydropower reservoirs and regulation structures on the Drava and other tributaries contribute to local flood attenuation, flow regulation, and water-resource management. Their operational influence becomes particularly relevant when coordinated with upstream systems in Slovenia and Austria and downstream requirements in Hungary and Serbia.

Drought and water scarcity are also emerging as increasingly important challenges. Extended dry periods observed in 2003, 2012, 2017, 2022, and 2024 have affected agriculture, ecosystems, navigation, and hydropower production. Climate-change projections indicate increasing temperatures, more frequent heat waves, reduced summer runoff, and greater variability in precipitation patterns. These developments are expected to increase the occurrence of both flood and drought extremes, requiring more flexible and integrated water-management approaches.

From a transboundary perspective, Croatia occupies a key position within several internationally shared river systems. Effective management of future hydrological extremes will therefore depend on continued cooperation through mechanisms such as the International Sava River Basin Commission (ISRBC), the ICPDR framework, and bilateral agreements with neighbouring countries. Improved forecasting, enhanced floodplain restoration, adaptive reservoir operation, and integrated flood and drought management will be essential components of long-term resilience in the Croatian section of the Danube River Basin.

3.3. Lower Danube Region

The Lower Danube Region, including Romania, Bulgaria, and Ukraine, is defined by low hydraulic gradients, long flood-wave travel times, large floodplain systems, and strong sediment and deltaic dynamics, which are critical for ecosystem functioning and biodiversity. Floods in this region are generally slower than in mountain basins but can become spatially extensive and operationally complex due to backwater effects, channel–floodplain interactions, which are essential for natural retention, habitat connectivity, sedimentation, and delta processes. This part of the basin also includes some of the most important transboundary interfaces, including ecologically sensitive areas such as the Danube Delta, in the entire Danube system.

3.3.1. Romania

Romania has one of the most extensive and diversified hydraulic infrastructures, which has significantly modified natural river dynamics and floodplain connectivity in the Danube Basin. It includes large multipurpose dams, smaller locally managed dams and polders, nearly 9,600 km of levees, water-diversion systems, hydraulic complexes, and a broad range of river training and bank-stabilization works. This infrastructure reflects both long-standing exposure to floods and the country's need to balance flood control with hydropower, irrigation, water supply, navigation, and recreation.

Romania's flood-risk planning under successive EU Floods Directive cycles demonstrates a progressive expansion in scope. Initial APSFR identification focused on large historical fluvial floods, while later cycles incorporated pluvial flooding, urban flooding, infrastructure failure, and more event-specific local assessments. This evolution confirms that flood risk in Romania is multi-dimensional and spatially heterogeneous, including ecosystem and hydromorphological aspects. Some regions are dominated by large river floods, while others are more sensitive to flash floods, pluvial events, or failures in existing flood-defence systems.

Romania's river-basin diversity is particularly important from a scoping perspective. Someș–Tisa and Crișuri are influenced by mountain runoff and transboundary upstream dynamics; Mureș and Banat combine engineered control with strong tributary inputs; Olt and Argeș–Vedea are highly regulated and depend heavily on reservoir operation; Siret and Prut–Bârlad show strong atmospheric and transboundary controls; Dobrogea–Litoral is sensitive to short-duration flash floods and coastal drainage constraints; and the Danube lower course and delta introduce large-scale backwater, sediment, and navigation issues.

The Romanian pilot sites of Someș–Tisa and Crișuri provide especially useful contrasts. Someș–Tisa represents a mountain-influenced and partly natural system with strong transboundary Tisza connectivity, high orographic variability, and significant though not dominant storage regulation. Crișuri, by contrast, is more heavily engineered, with dense regulation, polders, inter-basin transfers, and extensive dike systems. Together they illustrate two distinct but complementary Romanian flood-management contexts: one shaped by compound mountain-to-plain transitions, the other by structural control and regulated lowland hydraulics. In both cases, aging dikes, fragmented management responsibilities, growing climate pressure, and the need for integrated flood-risk management remain major strategic issues.

3.3.2. Bulgaria

The Bulgarian Danube River Basin District covers the northern part of the country and represents the national Danube component under both the Water Framework Directive and the Floods Directive. It is dominated by plains and lowlands, with agriculture as the main land use, which influences runoff, water demand, and ecosystem conditions, but it also includes important mountainous source areas, especially in the Iskar and Ogosta systems. Hydrologically, floods are commonly linked to snowmelt, prolonged rainfall, or combined river–rainfall processes, while climate projections indicate increasing temperatures and growing intensity in short-duration heavy precipitation.

A notable feature of the Bulgarian Danube Basin is the coexistence of relatively abundant national water resources with major operational inefficiencies, including very high losses in public water-supply systems. Water use is strongly shaped by industry, particularly cooling water demands such as those associated with Kozloduy Nuclear Power Plant. At the same time, parts of the basin face seasonal water stress and increasing drought sensitivity.

Flood-risk assessment has identified a set of significant APSFRs, including both riverine and urban pluvial contexts, as well as zones exposed to dam-related and infrastructure-related flood hazards. Systems such as the Iskar basin early warning platform illustrate a growing emphasis on digital monitoring and operational preparedness. In scoping terms, Bulgaria's Danube Basin District represents a lowland, infrastructure-dependent system where future resilience depends not only on structural protection but also on restoration of natural retention capacity and ecosystem-based approaches to climate adaptation, reduction of water losses, improved dam safety, and more effective urban flood management.

3.3.3. Ukraine

The Ukrainian contribution to the Danube Basin is centred on the rivers of Transcarpathia, as well as the upper Prut and Siret systems. These basins are highly relevant to the

Danube because they form major upstream source areas for transboundary flood generation. The Transcarpathian region, dominated by the Ukrainian Carpathians and adjacent lowlands, is one of the most flood-prone regions in Europe. Rivers such as the Tisza, Latorytsia, Uzh, Borzhava, and Rika display typical mountain-river behaviour in their upper reaches: steep gradients, rapid runoff concentration, narrow valleys, and intense sensitivity to orographic rainfall.

Floods in Transcarpathia develop quickly, with level rises of 1.5 to 2.5 metres within hours in some cases, and often affect multiple rivers simultaneously. The combination of strong orographic precipitation, arc-shaped mountain barriers, and low natural buffering capacity produces highly dynamic flash-flood and rain-on-snow regimes. Historical floods in 1998 and 2001 were particularly destructive, causing large-scale damage to settlements, ecosystems, and infrastructure. These events demonstrate that in the Upper Tisza context, Ukraine acts as a critical flood-generation region with strong downstream ecological and hydrological implications.

The Prut and Siret basins in western Ukraine show similar mountain-to-lowland transitions, with spring snowmelt floods, intense summer rainfall floods, unstable winter ice conditions, and strong erosion and landslide sensitivity. These rivers are transboundary by definition and underline the need for coordinated observation, forecasting, ecological monitoring and information exchange between Ukraine, Romania, Moldova, Hungary, and Slovakia. From the perspective of the LAREDAR scoping study, Ukraine's pilot areas highlight the importance of upstream hydrometeorological processes, rapid hydrological response, and real-time monitoring for reducing downstream risk across the wider Danube Basin.

3.4. Comparative Scoping Conclusions

Across the Danube Basin, hydrological extremes exhibit strong regional contrasts but are connected by common systemic drivers. In the Upper Danube, flood risk is shaped by Alpine runoff, tributary synchronization, and rapid wave generation. In the Middle Danube, the dominant features are lowland hydraulics, prolonged flood-wave durations, transformed floodplains, reduced ecological connectivity, and the coexistence of flood and drought pressures. In the Lower Danube, backwater processes, sediment dynamics, extensive levee systems, and deltaic interactions become increasingly important.

Several cross-cutting conclusions emerge from the chapter. First, transboundary dependence is a defining feature throughout the basin. Flood and drought conditions in downstream countries are directly influenced by upstream precipitation, snowmelt, reservoir operation, and forecast-based regulation. Second, infrastructure plays a central yet differentiated role, while also influencing ecosystem structure and function. In some regions, especially Austria, Slovakia, Hungary, Romania, and Bulgaria, highly developed hydraulic systems provide significant management capacity but also create dependency on ageing structures, limit natural ecosystem resilience, and coordinated operation. In others, especially upstream mountain basins in Ukraine and parts of Slovenia, natural hydrological dynamics remain dominant and require strong forecasting and preparedness rather than large-scale structural control alone.

Third, climate change is amplifying both flood and drought risks and increasing pressure on ecosystems. Rising temperatures, more variable precipitation, reduced snow reliability, and increased heatwaves are already changing runoff seasonality, drought severity, and event intensity. Fourth, integrated flood and drought management is becoming increasingly necessary. Many of the same systems - reservoirs, barrages, transfer canals, floodplains, and operational rules - must now serve multiple objectives, including flood attenuation, ecological status improvement, biodiversity support, irrigation, and hydropower, navigation, and drought mitigation.

Finally, the chapter confirms that the Danube Basin should be approached as a multi-hazard, multi-scale, and multi-country system. For the LAREDAR project, this implies a strong need for interoperable datasets, shared forecasting frameworks, cross-border early warning, improved understanding of retention functions, modernization of ageing infrastructure, and broader use of integrated flood-risk management approaches that combine structural, operational, spatial, and ecosystem-based measures.

4. Types of lakes and reservoirs

Understanding the role of lakes, reservoirs, and retention structures is a fundamental component of the LAREDAR project, particularly in the context of integrated flood and drought risk management within the Danube River Basin (DRB), including ecosystem status and hydromorphological processes. In line with the ICPDR Danube Flood Risk Management Plan, flood retention structures—whether artificial or natural—are defined as systems capable of temporarily storing water in order to delay and attenuate flood peaks and reduce downstream impacts, while also influencing flow regimes, sediment transport, and ecological conditions. These include reservoirs, detention basins, polders, wetlands, and floodplains, all of which contribute to modifying hydrological extremes at different spatial and temporal scales.

Beyond engineered systems, the concept of natural water retention measures is increasingly emphasized. These rely on enhancing the storage capacity of landscapes, aquifers, and ecosystems, as well as restoring natural river morphology and floodplain connectivity as key elements in improving ecological status. In practice, effective flood and drought management in the DRB requires a combination of structural, nature-based, and hybrid solutions, supported by coordinated planning, shared knowledge, and transboundary cooperation.

Within this framework, the systematic characterization of lakes and reservoirs is essential for the LAREDAR scoping study. Given the diversity of hydraulic structures and natural water bodies across the basin, a harmonized classification approach was required to support cross-border comparability, data integration, and pilot area analysis. This led to the development of a structured determination key and a standardized data collection methodology.

4.1. Typology and Determination Framework

The classification of lakes and reservoirs within LAREDAR is based on a decision-tree approach developed through an iterative process involving literature review, previous project experience (e.g., DAREFORT, DANUBE FLOODPLAIN), and continuous consultation among project partners. This framework provides a consistent method for identifying, categorizing, analysing water bodies, and their ecological and hydro morphological characteristics across heterogeneous pilot areas.

The determination process begins with the collection of spatial and technical information, including hydrographic datasets, maps, satellite imagery, and management documentation. Based on these inputs, operators apply a dichotomous decision tree, progressing from general structural characteristics to more detailed functional attributes.

The first level of classification distinguishes between **natural and artificial systems**, based on the presence of anthropogenic elements such as dams, weirs, or control structures that modify the natural hydraulic regime. This distinction is critical, as it reflects fundamentally different mechanisms of water retention, operational control, and management potential.

Within artificial systems, a second key differentiation concerns the **relationship to the river system**. Structures may be located directly within the main channel, where they influence flow dynamics and water levels, or outside the channel, typically in floodplains or tributary catchments, where they function as lateral storage systems supplied by runoff or controlled diversion.

Further classification depends on hydraulic behaviour and operational characteristics. Floodplain structures are differentiated between **permanently inundated managed lakes**, where water levels are actively regulated, and **dry retention basins or polders**, which are only filled during high-flow events and primarily serve temporary storage functions. In contrast, in-channel structures are categorized based on the degree of controllability, distinguishing between actively managed reservoirs and more passive storage systems.

Natural environments are also explicitly incorporated into the typology. These include both **permanent natural water bodies** (e.g., natural lakes or channel depressions) and **temporarily inundated systems** such as wetlands and floodplains. Although these systems play a significant role in passive flood attenuation, their extent and storage capacity are often difficult to quantify. To address this, the FEM (Floodplain Evaluation Method) approach was adopted to support consistent delineation and assessment.

The resulting classification framework defines nine categories of water bodies and retention systems, ranging from highly controllable river reservoirs to unmanaged lakes and natural retention areas. This typology provides a common reference for analysing how different structures contribute to flood mitigation and drought resilience across the pilot areas.

4.2. Standardized Data Collection: LAREDAR Questionnaire

Building on the classification framework, the LAREDAR project developed a comprehensive questionnaire to standardize data collection on lakes and reservoirs. The objective is to create a harmonized and interoperable dataset supporting hydrological modelling, spatial analysis, and decision-making across the DRB.

The questionnaire is structured into eight thematic sections, covering identification, technical characteristics, operational behaviour, and governance aspects. It combines qualitative descriptions with quantitative parameters, ensuring both comparability and contextual understanding. The inclusion of geodetic (WGS84) and altimetric references enables direct integration into GIS environments and supports spatial analysis at multiple scales.

The first section captures **general information**, including naming conventions (important in transboundary contexts), classification according to the typology, geographic coordinates, age, ownership, and operational responsibilities. It also identifies the primary and secondary functions of each structure and its general role in flood management.

The second section focuses on **structural characteristics**, including construction type, hydraulic works, discharge capacities, dimensions, and storage volumes. These parameters are essential for evaluating the physical capacity of reservoirs and their potential role in water retention.

Sections three and four address **flood mitigation and water scarcity functions**, respectively. They distinguish between passive and active management, document operational rules such as pre-release strategies or controlled discharges, and capture the role of reservoirs in maintaining ecological flows and supporting downstream water availability during drought conditions.

The fifth section examines **transboundary aspects**, identifying cross-border interactions, cooperation agreements, and upstream–downstream dependencies. This is particularly relevant in the Danube Basin, where water management decisions in one country can have significant impacts elsewhere.

The sixth section focuses on **challenges and risks**, including infrastructure ageing, sedimentation, environmental constraints, and potential failure scenarios. This provides a basis for assessing system vulnerabilities under extreme conditions.

The seventh section addresses **data availability and monitoring**, documenting the accessibility of datasets, types of measurements collected, and the presence of advanced tools such as LiDAR. This is crucial for evaluating the readiness of systems for integration into digital platforms and early warning frameworks.

Finally, the eighth section collects **recommendations and lessons learned**, supporting knowledge exchange and the identification of best practices across pilot areas.

Overall, the questionnaire represents a key methodological tool within LAREDAR, enabling a consistent, scalable, and extensible inventory of lakes and reservoirs across the basin.

4.3. Pilot Area Applications and Case Studies

The application of the typology and questionnaire in pilot areas demonstrates the diversity of reservoir types and operational strategies across the DRB.

In Germany, reservoirs such as **Forggensee** and **Sylvensteinspeicher** represent highly controllable systems with significant flood attenuation capacity. Their operation is based on forecast-driven pre-release strategies combined with peak retention, highlighting the importance of timing and dynamic management. These reservoirs also provide multi-purpose benefits, including hydropower generation and ecological flow support, illustrating the multifunctional nature of modern reservoir systems.

In Austria, the Mur River cascade consists primarily of **run-of-river hydropower plants** with limited storage capacity and low controllability. Their role during floods is mainly to pass flows downstream, demonstrating that not all hydraulic structures contribute significantly to flood retention. This underscores the importance of distinguishing between structural presence and functional effectiveness within the classification framework.

In Hungary, **Lake Tisza** exemplifies a multi-purpose reservoir system with a strong emphasis on water regulation, irrigation, and ecological management. While its flood retention capacity is limited compared to dedicated flood-control reservoirs, it plays a key role in balancing water availability and supporting low-flow conditions. Its operation reflects the complexity of managing competing objectives within a highly regulated lowland system.

In Serbia, the **Novi Bečej** structure operates primarily as a backwater regulation system supporting the Danube–Tisza–Danube canal network. During floods, it transitions to near-free flow conditions, indicating minimal retention function. However, it plays a critical role in water redistribution, navigation, and drought management, highlighting the multi functionality of hydraulic infrastructure in lowland environments.

These case studies illustrate that reservoir effectiveness in flood mitigation depends not only on structural characteristics but also on operational strategies, system integration, and basin position.

4.4. Key Challenges and Scoping Insights

The analysis highlights several cross-cutting challenges relevant to the LAREDAR project.

First, **data availability and accessibility** remain a major constraint. In many cases, detailed technical information is restricted due to ownership, security, or institutional limitations. While some partners benefit from formal agreements enabling access to high-resolution datasets, others must rely on publicly available information, leading to inconsistencies in data quality and completeness.

Second, **heterogeneity of structures and functions** complicates comparative analysis. Reservoirs range from highly controlled systems with significant storage capacity to passive or run-of-river structures with limited flood mitigation potential. This diversity reinforces the need for a robust and flexible classification framework.

Third, **operational coordination and forecasting** emerge as critical factors in determining effectiveness. Case studies demonstrate that proactive management, particularly timely pre-release based on reliable forecasts, can significantly enhance flood attenuation.

Fourth, **infrastructure ageing, sedimentation, and maintenance constraints** represent systemic risks across many pilot areas. These factors reduce operational capacity and increase vulnerability during extreme events.

Finally, **transboundary coordination** remains a central challenge. Given the interconnected nature of the Danube Basin, effective flood and drought management requires harmonized data sharing, coordinated reservoir operation, and integrated planning across national borders.

4.5. Implications for LAREDAR

From a scoping perspective, the classification and assessment of lakes and reservoirs provide a critical foundation for achieving LAREDAR objectives, particularly in relation to Deliverable D2.1.1.

The developed typology and questionnaire enable:

- A harmonized inventory of retention structures across pilot areas
- Improved understanding of their role in flood mitigation and low-flow support
- Identification of data gaps and monitoring needs
- Enhanced integration of structural and nature-based solutions
- Support for transboundary cooperation and decision-making

Ultimately, the findings confirm that lakes, reservoirs, and natural retention systems are key components of basin-scale resilience. Their effectiveness depends not only on physical characteristics but also on operational strategies, data availability, and institutional coordination. The LAREDAR framework provides the tools to systematically assess these factors and to support the development of integrated, adaptive, and transboundary water management solutions in the Danube River Basin.

The participants identified some of the partners. Those with pilot areas (LP1, PP3, PP5, and PP9) focused on their structures located in these areas (PP4 has no structures on the riverbank). The other participants selected structures representative of the objective of Deliverable D2.1.1. (PP2 and PP9).

Germany (PP2 TUM)

Forggensee is a highly controllable reservoir in the Lech basin, which plays a major role in flood protection through cascade coordination (Füssen → Landsberg → Augsburg), in addition to hydroelectric power generation and recreational uses. The management strategy is based on rapid pre-releases followed by peak retention to cap peaks, with significant mitigation during the events of 1999 and 2005, according to the authorities' analyses. The configuration includes a clay/moraine core embankment dam, a radial gate spillway, and a low outlet, with discharge capacities of around 570 m3/s at peak and 370 m3/s at low (including approximately 150 m3/s through the turbines), and volumes ranging from 12 million m^3 to 168 million m^3, including 130 to 150 million m^3 allocated to flood management. The management mode is active, based on forecasts, and feedback highlights that the timing of pre-release is more important than volume alone in terms of peak reduction efficiency.

The Sylvensteinspeicher is a critical retention reservoir for the Isar River, protecting Bad Tölz and Munich, with an earth dam structure, a controlled spillway, and a low outlet with typical capacities of approximately 610 m^3/s at the spillway and 620 m^3/s at the bottom outlet. Retention volumes range from 4 million m^3 to 124 million m^3, with 90 million m^3 maneuverable and 85 million m^3 explicitly allocated to flood protection, representing a protection share of approximately 68%. Operational management adopts early lowering, peak retention, and gradual releases, with peak reductions confirmed during the 1999/2005 events. During low water periods, a minimum ecological flow of approximately 5 m^3/s is ensured, with seasonal indications of 10 m^3/s in winter and 20 m^3/s in summer at Bad Tölz, and a volume reserved for low water levels of around 28 million m^3. The recommended improvements concern snow/melt modeling, forecast accuracy, and dynamic storage optimization, with the key lesson being early and decisive pre-release.

Austria (PP3 BOKU)

The facilities on the Mur in Styria are run-of-river power plants with low controllability and no dedicated storage for flood peak reduction (flood control storage). Their role during floods is to transfer flow through spillway gates with the turbines shut down at extremes, as in the case of KW Spielfeld, commissioned in 1982, has two horizontal Kaplan turbines (installed capacity ≈13 MW, annual production ≈67.7 GWh) and a fish pass, with flood operation based on passage through the spillway and shutdown of the turbines. The mitigation role is limited by the run-of-river design, and the identified risks relate to dam overflow and debris/sediment accumulation. Detailed retention data is not generally public, although basic information is available, and lidar surveys are available through the Styrian authorities. Recommendations focus on increasing spillway capacity or creating adjacent detention areas, improving gate automation and debris/sediment management, and strengthening coordination of the Mur cascade as part of the Mura–Drava–Danube Transboundary Biosphere Reserve, which supports ecological continuity and sustainable approaches.

Hungary (LP1 KÖTIVIZIG)

Lake Tisza is an artificial reservoir designed to regulate the flow and water levels of the Tisza River, provide irrigation and water supply, with additional functions related to tourism, conservation, and preservation of wetlands and biodiversity. The structure combines a concrete dam, earthen closure dikes, and natural low-lying areas, with management tools including an adjustable gate spillway, a lock, and turbine discharges. Flood operation is governed by flow thresholds, with conditional turbining up to approximately 1,700 m^3/s, engagement of plain devices around 2,500 m^3/s, and cessation of production beyond that, with the primary function being regulation rather than flood wave retention. The maximum flow observed is 2,950 m3/s. The good practices include closing the spillways during floods to concentrate flows in the main channel, opening the low-level passages above 2,500 m3/s, and sequential post-peak closure to safely restore impoundment. Capacities and volumes are characterized by an area of approximately 127 km^2, with operational volumes ranging from approximately 68 million m^3 when the water level reaches a reference height of 560 cm to 89 million m^3 for a level of 750 cm in maneuverable volume. This corresponds to 10 to 15% of the total volume. Operational coordination is carried out with the actors of the Tisza–Körös system, and monitoring combines public data (water levels, discharges) with information accessible under agreement (bathymetry, technical documents), including tracking of water levels, discharges, precipitation, sedimentation, water quality, gate operations, and structural movements. Terrestrial LiDAR surveys and bathymetric measurements are used when depths exceed 2.5 to 3 m. The identified challenges relate to sedimentation, ageing infrastructure, and budgetary constraints. Recommendations include reinforcement of dikes, adaptation of protections to the operational level of 750 cm, and installation of a floating debris barrier at the Kisköre dam.

Serbia (PP9 JCWI)

The upstream section of Novi Bečej is a backwater area that feeds the Danube–Tisa–Danube (DTD) system by gravity for irrigation, industry, and urban water supply, with support for navigation and fisheries. The diversion capacity to the DTD reaches up to 120 m^3/s. The Novi Bečej structure is a concrete dam, supplemented by closure dikes in the plain and a navigation lock, equipped with radial gates with valves operating as spillways and bottom structures. During floods, operation consists of completely raising the gates and switching to a quasi-free flow regime without retention. The flow capacity in quasi-free flow configuration allows for the evacuation of approximately 4,750 m3/s (all gates raised), with design floods ranging from 4,200 m3/s (HQ100) to 6,400 m3/s (HQ1000), and a maximum recorded flow rate of 3,720 m3/s. This operating mode is active for regulating backwater up to approximately 1,080 m3/s, then switches to near-free flow. The upstream dikes are designed for approximately 4,100 m3/s with a 1.0 m freeboard. During low water periods, the backwater is maintained to feed the DTD, with a minimum ecological flow of around Q95≈65 m3/s and a low water reserve volume of 50 million m3. Public monitoring covers flows (Senta station) and levels (including Novi Bečej), while detailed technical documentation is restricted, with lidar capabilities available to the competent authorities. Coordination and management practices include emergency and defense plans, ice management measures, and cooperation with upstream and downstream structures and authorities for flood and low water management.

The primary challenge in data acquisition stems from the restricted accessibility of technical information, which is available only under formal agreements. This applies, for instance, to partners such as PP1 and PP9, who are directly involved in facility operations. Other partners, such as PP2, benefit from established agreements that grant detailed access to technical datasets. Conversely, partners like PP3 have only limited access to asset data due to its private nature and must rely on publicly available sources in the absence of agreements with the operating entities.

5. Rules of operations of the dams along the Danube River Basin

Dam and reservoir operation in the Danube River Basin (DRB) is a critical component of integrated water management, linking flood protection, hydropower generation, irrigation, navigation, ecological flow maintenance, and water supply, while also influencing hydromorphological processes and biodiversity status. In the context of LAREDAR, the analysis of operational rules is particularly relevant because it reveals how existing infrastructure can support or constrain coordinated responses to floods and droughts, especially in transboundary settings.

Across the surveyed countries, operational frameworks are shaped by a combination of legal mandates, technical rules, institutional responsibilities, and hydrological conditions. Although the DRB countries share common reference points through EU water legislation and international basin cooperation, the practical application of dam operation rules varies considerably. These differences concern not only who manages and supervises reservoirs, but also how flood prevention is embedded in operation rules, how monitoring is organized, how transparent operational data are, and to what extent climate adaptation is already being integrated into existing systems.

From a scoping perspective, the review confirms that the DRB already contains a substantial operational and institutional basis for coordinated reservoir management, including environmental and ecological considerations, but that this basis remains uneven in maturity, transparency, and digitalization. This has direct implications for LAREDAR, particularly with regard to data harmonization, cross-border communication, and the identification of opportunities to improve flood and drought resilience through better operational coordination.

5.1. Which are the subjects in your country involved in the management of the reservoirs?

Reservoir management in the surveyed countries is organized through a multi-level governance structure involving ministries, water agencies, dam operators, environmental bodies, hydrometeorological institutions, safety authorities, and emergency-response organizations. This reflects the multifunctional role of reservoirs in the DRB, where a single structure may simultaneously serve hydropower generation, flood mitigation, irrigation, ecological regulation, recreation, and municipal or industrial water supply whilealso influencing hydromorphological processes and biodiversity.

In all participating countries, the national ministries responsible for environment, water, energy, or infrastructure define the overarching legal and policy framework. These ministries are supported by specialized public authorities or basin organizations that handle operational management, maintenance, regulatory oversight, and planning. In parallel, hydropower companies and water utilities often act as direct operators of dams and reservoirs, especially where the main function of the structure is energy production or water supply.

Environmental oversight and technical safety monitoring are typically performed by dedicated agencies, inspectorates, or hydrometeorological services. These bodies provide control over compliance, water-quality issues, ecosystem status, structural integrity, and hydrological monitoring, and they are often closely linked to flood forecasting and emergency response. In several countries, civil protection and interior ministries also play a formal role, particularly in emergency preparedness, flood response, and disaster coordination.

The country responses show both commonality and institutional variation. Hungary relies heavily on regional water directorates and state water-management structures. Germany and Austria demonstrate strong integration between water authorities, hydropower companies, and safety bodies, while Slovenia stands out for its particularly broad multi-sectoral governance, including inspectorates and civil protection authorities. Romania, Slovakia, and Serbia emphasize the role of national water management companies and state enterprises, while Bulgaria illustrates a complex system involving basin directorates, dam-safety supervision bodies, and sectoral ministries. Ukraine's framework remains strongly state-centered, with ministries, the State Agency of Water Resources, and hydrometeorological services playing central roles.

Overall, reservoir management in the DRB is clearly not the responsibility of a single actor, but of an interconnected system of institutions. This is highly relevant for LAREDAR, because effective communication, data exchange, and operational coordination during extreme events depend on how well these actors interact across administrative and sectoral boundaries.

5.2. Which are the subjects which are or will be involved in the communication process during the LAREDAR project?

The communication process envisaged within LAREDAR builds on this same multi-level governance structure. Across partner countries, the key actors identified for project communication are national and regional water authorities, environmental ministries and agencies, dam and reservoir operators, scientific institutions, hydrometeorological services, and in some cases emergency and civil protection bodies.

A clear common pattern emerges: water-management institutions form the core communication backbone in all countries. This is expected, as they are responsible for operational control, flood-risk planning, reservoir management, and implementation of water-related legislation. Environmental and nature conservation authorities are also consistently involved, highlighting the fact that reservoir operation is not understood solely in technical terms, but also in relation to sustainability, ecological status, and climate adaptation.

In several countries, particularly Austria, Hungary, and Slovenia, energy-related actors are also explicitly included. This reflects the strategic importance of hydropower and the fact that reservoir operation is often closely linked to electricity production. In such contexts, LAREDAR communication must bridge public-interest objectives such as flood protection with commercially sensitive operational realities.

The partners also reveal national differences in communication scope. Slovenia proposes the broadest stakeholder range, including civil protection, inspectorates, finance-related institutions, and NGOs, suggesting a strongly cross-sectoral communication culture. Romania focuses on national water authorities and hydrological institutions, while Serbia centers on regional public water management companies. Ukraine places stronger emphasis on the legal and regulatory framework, indicating that communication around LAREDAR is also seen as an opportunity to align national practice with EU water directives and international standards.

From a scoping-study perspective, this comparison suggests that LAREDAR already benefits from a strong institutional basis for communication across the DRB. At the same time, it also shows that communication cultures differ. Some countries are oriented more toward administration and technical operations, while others adopt a broader multi-stakeholder approach and consider environmental and nature conservation conditions more inclusively. These differences should be seen not as obstacles, but as opportunities for knowledge exchange and institutional learning.

5.3. List the legislation defining the domain

The legal framework governing dam and reservoir management across the surveyed countries is robust, but multi-layered and diverse. In all cases, the core of the regulatory system is formed by a national Water Act or equivalent legislation, which defines the use, protection, and management of water resources and hydraulic structures. Around this core, countries have developed additional legislation covering dam safety, flood-risk reduction, environment and nature conservation, emergency response, civil protection, and in some cases construction law and energy regulation.

A strong point of convergence across the DRB is the alignment with European legislation, particularly the Water Framework Directive (2000/60/EC) and the Floods Directive (2007/60/EC) as well as the Birds Directive (2009/147/EC) and the Habitats Directive (92/43/EEC). These directives provide a shared normative basis for water governance, river basin planning, and flood-risk assessment. Even in countries outside the EU context, such as Ukraine, these directives are referenced as important benchmarks for legal and institutional alignment.

Nevertheless, the level of detail and sectoral integration varies from country to country. Hungary and Slovakia rely on clearly identified central water laws supported by implementing decrees. Germany combines federal and state water laws with strong technical standards, including dam-specific guidelines. Austria and Slovenia illustrate more integrated legal systems, where water legislation is closely linked to environmental policy, construction law, and climate-related regulation. Romania and Bulgaria have detailed legislation on dam operation, safety, monitoring, and technical rules, while Serbia presents one of the most comprehensive frameworks, combining laws on waters, disaster risk reduction, emergency management, planning, construction, and dam safety.

For LAREDAR, this legal review is particularly important because it shows that the participating countries already share a broad legislative foundation for cooperation, but differ in institutional adaptation, technical specificity, and implementation practice. This creates favourable conditions for transboundary exchange on best practices, but also means that harmonized operational approaches will need to account for national legal differences.

5.4. Rules of operations of the dams and related reservoirs

Rules of operation, also referred to as operating rules, rule curves, or reservoir operating policies, define how dams and reservoirs are managed under different hydrological, technical, environmental, and emergency conditions. They govern target water levels, release regimes, flood-storage allocation, spillway activation, turbine use, and downstream discharge objectives. In multipurpose systems, these rules are essential because reservoirs must simultaneously satisfy competing objectives, including flood control, hydropower production, irrigation, ecological flow maintenance, navigation, and water supply.

From the perspective of LAREDAR, operation rules are particularly relevant in flood situations. Key questions concern which reservoir levels are maintained at different river discharges, what downstream target discharges are defined, which spillways or bottom outlets are activated under flood conditions, and what volume is reserved specifically for flood attenuation. These operational aspects directly influence the capacity of reservoirs to reduce downstream flood peaks and to contribute to coordinated basin-scale risk management.

It is also important to distinguish between operation under normal discharge conditions and operation during flood events. In many hydropower systems, regular operation is shaped by electricity-market conditions and therefore may involve confidential or commercially sensitive rules. LAREDAR's interest lies primarily in the public-interest domain: flood-related operation, emergency procedures, and the use of reservoirs for reducing hydrological risk.

5.4.1. Operation of the reservoirs/dams

Across the partner countries, reservoir operation is generally defined through water permits, operating instructions, or concession frameworks. These documents specify discharge limits, target water levels, seasonal operating conditions, and safety-related procedures. In most countries, large reservoirs remain under public ownership or public control, even when hydropower companies or utilities are involved in daily operation.

Concession systems are applied unevenly. Austria and Slovenia provide the clearest examples of formal concession-based operation for hydropower structures, often linked to licensing fees or concession payments. Slovenia is especially notable for its transparent "Water Book," where permits and water rights are formally recorded. By contrast, Hungary, Romania, and in many cases Germany report mainly state-owned or publicly regulated systems without concession payments for major flood-control structures. Serbia, Slovakia, and Bulgaria apply usage fees for public water resources rather than concessions in a strict sense.

The comparison also reveals major differences in transparency. Austria and Slovenia offer relatively better public access to permits and operational information, while in Hungary, Romania, Serbia, and some other countries such documents are generally not public because they are treated as critical infrastructure information. This uneven openness has direct relevance for LAREDAR, since it affects the possibility of comparing operational logic, modelling reservoir behaviour, and supporting cross-border understanding of how flood management functions in practice.

5.4.2. Flood prevention addressed in the rules of operation

Flood prevention is a central component of dam operation rules in all surveyed countries, but its degree of formalization, standardization, and accessibility differs significantly. In most countries, flood prevention is embedded in water permits, operating instructions, or reservoir-specific rules, often including flood-storage allocation, pre-lowering procedures, monitoring requirements, and emergency protocols.

Countries such as Germany and Austria apply detailed flood-management strategies for major reservoirs, including reservoir-specific storage assignment and pre-release procedures. Slovenia and Slovakia integrate flood rules into broader permit and decree systems, while Romania and Bulgaria emphasize erosion control, inspections, flood-risk planning, and operational measures linked to flood-risk management plans. Serbia stands out for its relatively formalized approach, combining hazard and risk mapping, operational conditions, monitoring, and public flood information systems. Ukraine indicates that flood prevention is the responsibility of reservoir owners and permitting authorities, although details remain less accessible.

A key scoping insight is that flood prevention is recognized everywhere as a legitimate and necessary function of reservoir operation, but that the operational maturity of this function varies. In some countries, reservoir-based flood mitigation is highly structured and supported by modelling and emergency planning. In others, it is embedded more generally within permit conditions or depends strongly on operator practice. For LAREDAR, this suggests strong potential for knowledge exchange on flood-oriented reservoir operation, especially in transboundary settings.

5.4.3. Monitoring of the operation of the reservoirs/dams

Reservoir and dam monitoring across the DRB is generally based on operator responsibility combined with state oversight. Typical monitoring methods include on-site sensors, telemetry systems, water-level and discharge measurements, technical inspections, structural assessments, and routine reporting. For larger dams, reporting and supervision requirements are often more stringent, including monthly or annual summaries and periodic expert inspections.

The partner responses show a spectrum of monitoring maturity. Hungary integrates monitoring into the national hydrometeorological system. Germany and Austria have strong regulatory oversight combined with hydrographic service support. Slovenia uses operator-based systems defined by permits, especially for larger dams. Serbia has a differentiated system, with more advanced tools mainly at hydropower structures. Slovakia operates a unified daily monitoring framework supported by sensors and SCADA, coordinated with the national hydrometeorological institute. Bulgaria presents one of the most advanced examples, using cloud-based platforms, remote devices, automatic alerts, and structural-health monitoring. Ukraine applies facility-specific monitoring based on technical operating rules.

Public access to monitoring data remains uneven. Some countries provide partial public access to hydrological information, while others restrict data because of safety and infrastructure concerns. This uneven availability affects the potential for transboundary operational transparency and system-wide learning.

5.4.4. Definition of the chain operation of the reservoirs

The concept of chain operation, coordinated management of multiple reservoirs within one river system or cascade, is of major relevance for flood-risk reduction, drought management, and hydropower optimization. However, the survey results show different levels of maturity across partner countries.

Hungary, Slovenia, Romania, and Slovakia report clearly defined chain-operation systems or methodologies. These are often embedded in national regulations, operational plans, or river basin management documents, and in some cases supported by hydrodynamic modelling and cost-benefit analysis. Austria appears to have partial or implicit arrangements depending on reservoir size and local practice. Germany indicates that chain-operation concepts are under development. Bulgaria reports coordination in some cascades, but without a formalized basin-wide protocol. Serbia and Ukraine could not provide sufficient information, largely due to limited data accessibility.

This uneven development is highly relevant for LAREDAR. It suggests that some parts of the basin already operate with cascade logic and coordinated reservoir management, while others rely more on site-by-site decision-making or informal coordination. Strengthening chain-operation concepts could therefore be an important avenue for improving basin-scale resilience.

5.4.5. The availability of data on reservoir operation

The availability of reservoir-operation data is one of the most critical issues identified in the review. Most countries provide at least basic hydrological information such as water levels, inflows, or discharges, either publicly or on request. However, detailed operational data, such as operating curves, technical rules, gate-management protocols, or flood-routing schemes, are generally restricted for safety, security, or institutional reasons.

Hungary, Germany, Austria, Romania, and Bulgaria provide partial access to basic data, while Slovenia indicates that detailed operational material is largely internal and institutionally fragmented. Serbia reports no public access to reservoir-operation data. For Slovakia and Ukraine, the picture remains less clear, though access appears limited. Bulgaria shows some progress through its open-data systems, but comprehensive transparency is still lacking.

From a scoping-study perspective, this means that one of the main barriers to transboundary comparison and coordinated modelling is not the absence of dams or operators, but the limited openness of operational information. LAREDAR therefore has an important role in identifying which data can realistically be shared, under what conditions, and how common approaches to data exchange could support risk management without compromising infrastructure security.

5.4.6. Climate adaptation process relative to the existing dams/reservoirs

Climate adaptation is increasingly recognized in reservoir and dam management across the partner countries, but the level of implementation differs substantially. Hungary, Germany, Romania, Slovakia, and Bulgaria report that climate adaptation is already integrated into national strategies or water-management planning, with emphasis on hydrological modelling, infrastructure safety, drought resilience, and revision of operational rules. Austria, Slovenia, and Serbia are at earlier stages, where adaptation is discussed, researched, or emerging in policy but is not yet fully embedded in operational practice. For Ukraine, no clear information was available.

Across the region, common adaptation challenges include ageing infrastructure, greater variability in inflows, more frequent floods and droughts, sedimentation, and insufficient funding for modernization. These issues confirm that adaptation is not only a technical problem but also an institutional and financial one. In many countries, the strategic direction is already present, but implementation remains uneven.

For LAREDAR, this is a key finding. The resilience of reservoir systems under climate change will depend not only on improved forecasting or revised rule curves, but also on coordinated investment, institutional learning, and basin-scale integration of climate-informed operation principles.

5.5. Scoping conclusions

The review of operational frameworks shows that dam and reservoir management in the Danube River Basin is predominantly state-regulated, though the balance between public control, operator responsibility, concession-based use, and public transparency varies by country. Shared reliance on EU water legislation and flood-risk frameworks provides a common strategic foundation, but operational practice remains heterogeneous.

Several conclusions are particularly relevant for LAREDAR. First, flood prevention is integrated into dam operation everywhere, but the degree of formalization and operational sophistication differs. Second, monitoring systems are widespread, but not equally developed or accessible. Third, chain-operation concepts exist in some countries as mature coordination tools, while in others they remain partial, informal, or under development. Fourth, reservoir-operation data are only partially available, which limits comparison, modelling, and cross-border operational learning. Finally, climate adaptation is increasingly recognized, but practical implementation is still incomplete in many parts of the basin.

Taken together, these findings confirm that operational rules are a central but under-harmonized element of reservoir governance in the DRB. For the LAREDAR project, this creates a clear field of action: to support exchange on best practices, improve understanding of flood-oriented reservoir operation, strengthen common approaches to data sharing and monitoring, and identify pathways toward more coordinated and climate-resilient dam operation across the basin.

6. Rules of Operations of the Dams and Related Reservoirs Addressed by the Pilot Cases of the LAREDAR Project

This chapter provides a preliminary synthesis of the operational rules governing selected dams and reservoirs within the LAREDAR pilot cases. The analysis is based on information collected from project partners, noting that the dataset remains provisional and subject to validation, as some inputs were translated from national languages using automated tools. Consequently, the findings presented here should be interpreted as an initial scoping-level assessment, to be refined in subsequent project phases.

The reviewed pilot cases offer a representative cross-section of operational practices across the Danube River Basin (DRB), encompassing multipurpose reservoirs, cascade hydropower systems, flood retention structures, and smaller diversion plants. The diversity of these systems highlights both the complexity and the potential for harmonisation of operational rules, particularly in the context of flood risk reduction, drought management, and climate adaptation.

6.1. Short description of pilot cases

The LAREDAR pilot cases span several key transboundary river systems in Central and Eastern Europe, including the Tisza, Mura, Morava, Isar, and Inn basins. These pilots collectively reflect a wide range of hydrological conditions, infrastructure types, and governance frameworks, thereby providing an appropriate testbed for evaluating reservoir operation strategies under varying environmental and institutional contexts.

The Kisköre Reservoir (Hungary), located on the Tisza River, represents a large multipurpose system with strong relevance for cross-border coordination with Romania and Serbia. Its operational focus includes flood mitigation, drought management, and water allocation for irrigation and ecological purposes. In Germany, the Sylvenstein Reservoir and the Töging–Jettenbach system illustrate advanced flood-control and hydropower-regulation practices, with emphasis on climate resilience and sediment management.

The Mura River system, addressed jointly by Austria and Slovenia, provides an example of a cascade of hydropower plants combined with natural retention areas, where flood mitigation depends not only on infrastructure but also on floodplain dynamics and cross-border coordination. Similarly, the Morava River basin (Slovakia–Austria) focuses on smaller reservoirs and tributary systems, highlighting the importance of distributed retention and coordinated management in lowland environments.

Additional pilot activities in Romania and Bulgaria address reservoirs with significant cross-border flood impacts, with particular attention to modelling, data availability, and operational harmonisation. Together, these pilot cases demonstrate that reservoir operation in the DRB cannot be understood in isolation, but must be analysed within a broader system of interconnected water bodies, governance structures, and hydrological processes.

From a scoping perspective, the pilot cases confirm the importance of integrating operational rules with data-driven approaches, particularly through the development of a common LAREDAR GIS platform. They also highlight that improved interoperability, transparency, and institutional coordination are key prerequisites for effective transboundary water management.

The comparative analysis of operational rules across pilot cases focused on key parameters, including reservoir levels under different discharge conditions, forecast-based operation, downstream target discharges, spillway activation thresholds, use of bottom outlets, and reserved flood-storage volumes. These criteria provide a consistent framework for comparing operational behaviour across diverse systems.

6.2. Rules on the Operation of the Kisköre Dam and Lake Tisza – Hungary

The Kisköre Reservoir (Lake Tisza) represents a typical multipurpose lowland reservoir, where operation is governed by a combination of seasonal regulation, ecological considerations, and flood management requirements.

6.2.1. General Operating Role

Lake Tisza, created by the Kisköre Dam in 1973, is a large artificial reservoir with a storage capacity of approximately 250 million m^3. Its operational role is highly multifunctional, encompassing drought mitigation, irrigation support, ecological preservation, flood control, navigation, hydropower generation, and recreational use. The reservoir plays a particularly important role in stabilizing water availability across the Great Hungarian Plain and supporting downstream systems such as the Körös basin.

6.2.2. Operational Oversight

Operational responsibility is shared between the hydropower operator (Tiszavíz Vízerőmű Kft.) and the regional water authority (Middle Tisza District Water Directorate), with additional involvement from environmental agencies, nature conservation bodies, law enforcement, and local authorities. This reflects a multi-actor governance structure typical of multipurpose reservoirs in the DRB.

6.2.3. Key Operational Rules and Parameters

The operation of Lake Tisza is characterized by a seasonal water-level regime. During the summer period, the reservoir is maintained at a relatively high level (approximately 88.57 m), while in autumn the water level is lowered by about 1.2 m to increase flood-storage capacity and support ecological processes such as sediment oxidation and water-quality improvement.

Water levels are controlled with high precision using segment gates, allowing fine regulation under normal conditions. However, a key feature of the Kisköre system is that it does not actively impound flood waves. Instead, during flood events, the reservoir passively fills, with water levels rising above the normal operating range.

6.2.4. Flood Management

Flood management at Kisköre is based on forecast-driven operation and coordination with national flood authorities. Flood defense takes absolute priority over all other uses, and operational measures focus on safely routing incoming flood waves while minimizing downstream risk. The reservoir acts as a temporary storage volume through controlled level increase rather than active retention through gate closure.

6.2.5. Hydropower and Water Regulation

The integrated hydropower plant (28 MW) operates within the broader water-management framework, producing renewable energy while maintaining downstream flow requirements. Additional operational functions include navigation support via locks and flow regulation through auxiliary structures.

6.2.6. Rules of Operation

The operational rules emphasize balancing multiple objectives: maintaining seasonal water levels, ensuring ecological conditions, supporting water use, and prioritizing flood safety. The absence of active flood impoundment distinguishes Kisköre from more strongly controlled reservoir systems and highlights its role as a regulated but relatively open system.

6.3. Dam exploitation rules – Slovakia (Gabčíkovo System)

The Gabčíkovo system represents a highly complex, large-scale, and strongly controlled hydraulic system, integrating navigation, hydropower, flood protection, considerations of fish pass, and transboundary water management.

6.3.1. General Operating Role

The Gabčíkovo–Nagymaros system (with only the Gabčíkovo stage currently operational) serves multiple strategic functions, including maintaining international navigation routes, regulating flows in the Danube, generating electricity, supporting water withdrawals, and ensuring environmental stability in adjacent areas.

6.3.2. Operational Oversight

Operation is managed through a centralized and highly coordinated dispatch system involving multiple control units (DRPP, DOaRV, VHD), supported by hydrological forecasts and real-time data. Daily and weekly operational planning ensures alignment between water-management and energy-production objectives.

6.3.3. Key Operational Rules and Parameters

Normal operation is defined within a specific flow range (up to approximately 5,700 m^3/s), with strict control of water levels and downstream discharge requirements. Minimum environmental flows are ensured, and water allocation is dynamically adjusted based on forecasts and operational needs.

6.3.4. Flood Management

Flood management is governed by a comprehensive set of plans and procedures, including coordination with upstream and downstream structures. The system provides high flexibility through multiple discharge pathways, including turbines, spillways, bypass systems, and navigation locks, allowing controlled routing of large flood volumes.

6.3.5. Safety and Restricted Zones

The system includes detailed emergency procedures, particularly for power-plant failures, which may require rapid redistribution of flows through alternative structures. Safety protocols also address navigation risks, ensuring that vessels and infrastructure are protected during operational disturbances.

6.3.6. Hydropower and Water Regulation

Hydropower operation is closely integrated with water management, using storage in the Hrušov reservoir and inlet canal to regulate flows. Both positive and negative flow regulation are applied, allowing dynamic adjustment of discharge while maintaining system stability.

6.3.7. Rules of Operation

Operational rules are highly detailed and technically sophisticated, reflecting the system's complexity. They include strict limits on flow variation rates, coordinated dispatching, and contingency procedures for system failures, making Gabčíkovo one of the most advanced operational systems in the DRB.

6.4. Dam exploitation rules – Bulgaria (Ogosta Reservoir)

The Ogosta reservoir illustrates a large multipurpose system with strong emphasis on safety regulation and emergency preparedness.

6.4.1. General Operating Role

Originally designed for irrigation, the reservoir now serves multiple purposes, including hydropower generation, flood control, and water management. Its large storage capacity (over 470 million m^3) provides significant potential for flood attenuation.

6.4.2. Documentation for operation

Bulgaria has introduced a comprehensive regulatory framework governing dam operation, including unified requirements for both large and small dams. Each dam must maintain a complete operational dossier covering its entire lifecycle, supported by detailed inspection and reporting requirements.

6.4.3. Flood zone

The potential flood zone of the Ogosta reservoir is extensive, affecting multiple settlements and critical infrastructure. This underlines the importance of continuous monitoring and preparedness.

6.4.4. Flood hazard, emergency readiness, and severe accident

The operational framework includes a clearly structured emergency management system with multiple stages: emergency readiness, flood hazard, and severe accident. Each stage is defined by specific triggers, such as rapid water-level rise, structural anomalies, or extreme inflow events, and is associated with predefined response measures.

This structured approach reflects a strong emphasis on risk management and safety, supported by detailed operational planning and coordination with regional authorities.

6.5. Dam exploitation rules – Slovenia (Ceršak Hydropower Plant)

The Ceršak small hydropower plant represents a different category of infrastructure: a small, ageing diversion-type facility with limited storage capacity and reduced flood-control functionality.

The plant operates primarily for energy generation and is characterized by relatively low installed capacity and limited operational flexibility. Its current condition highlights the challenges associated with ageing infrastructure, including structural degradation, maintenance needs, and the necessity for rehabilitation.

Despite its limited direct role in flood mitigation, the plant has indirect significance within the cascade system of the Mura River, particularly in maintaining downstream hydraulic conditions and ensuring continuity with upstream Austrian hydropower facilities.

6.6. Comparative assessment of operational rules

The comparison of pilot cases reveals significant differences in operational philosophy and technical capability across the DRB. Systems such as Gabčíkovo demonstrate highly controlled, centralized, and flexible operation with strong integration of hydropower and water management. In contrast, reservoirs like Kisköre operate with more limited control over flood waves, relying on passive storage and seasonal regulation. Ogosta represents a safety-oriented system with structured emergency procedures, while smaller facilities such as Ceršak highlight the constraints of ageing and low-capacity infrastructure.

Key differences are observed in flood operation strategies (active vs. passive control), discharge management, use of bottom outlets, and allocation of flood-storage volumes. Governance structures also vary, ranging from centralized dispatch systems to multi-actor coordination frameworks.

6.7. Scoping conclusions

The pilot-case analysis confirms that reservoir operation in the Danube River Basin is highly heterogeneous, reflecting differences in infrastructure type, operational objectives, governance frameworks, and technical capacity. At the same time, common elements can be identified, including the prioritization of flood safety, the integration of multiple water uses, and the increasing importance of real-time monitoring and forecast-based operation.

For LAREDAR, these findings highlight several key opportunities. First, there is strong potential to harmonize operational concepts, particularly in relation to flood management and transboundary coordination. Second, the diversity of systems provides valuable learning opportunities, allowing partners to exchange best practices across different operational contexts. Third, the integration of operational data into a common platform will be essential for improving system-wide understanding and supporting decision-making.

Ultimately, the pilot cases demonstrate that improving reservoir operation is not only a technical challenge, but also an institutional and data-related one. Addressing these dimensions will be critical for achieving LAREDAR's objective of enhancing climate resilience and coordinated water management across the Danube basin.

7. Possible functions and transboundary effects of lakes and reservoirs

This chapter synthesizes the main findings emerging from the third questionnaire and outlines the relevance of lakes and reservoirs for future modelling analyses within the LAREDAR project. Across the Danube River Basin, lakes and reservoirs perform a wide range of hydrological, ecological, and socio-economic functions. Their importance extends beyond local water management, as they can alter flood-wave propagation, low-flow conditions, sediment continuity, and groundwater recharge at broader basin scales, including across national borders.

From a scoping perspective, the role of lakes and reservoirs must be understood in relation to both their physical characteristics and their operational regime. Storage volume, outlet capacity, rule curves, seasonal water-level management, and integration within cascade systems all influence whether a water body attenuates flood peaks, supports sediment balance and drought management, mitigates biodiversity challenges, or modifies downstream hydrological conditions. At the same time, their effects are not uniform: they vary with catchment size, event magnitude, antecedent wetness, and the degree of river regulation and floodplain modification in the wider basin.

The international literature and partner contributions confirm that anthropogenic changes to river systems, including channel regulation, floodplain disconnection, dam construction, and land-use change, have significantly altered flood regimes over time. In this context, lakes and reservoirs may serve both as mitigating structures and as components of broader hydromorphological transformations. They can reduce or eliminate smaller and medium floods directly downstream, attenuate selected design events, and in some cases support ecological or water-supply releases during drought. However, these effects diminish with distance downstream and may be offset by cumulative basin processes.

For LAREDAR, this means that future modelling should not only assess individual reservoirs in isolation, but also evaluate their role within cumulative and transboundary hydrological systems. Particular attention should be given to storage-effect decay downstream, cascade interactions, sediment retention and balance and the trade-offs between flood mitigation, hydropower, biodiversity requirements, and low-flow support.

7.1. Austria

The Austrian contribution highlights the broader hydrological context in which reservoirs operate. Flood regimes are not only shaped by reservoirs alone, but by the cumulative interaction of catchment- characteristics, scales changes, river engineering, land-use, and climate change. In this framework, lakes and reservoirs are one of several drivers that modify flood peaks and flood shapes.

A key analytical point is that hydrological change depends strongly on scale. River training and bed modification typically increase flood peaks in smaller and medium-sized events by reducing hydraulic roughness, shortening flow paths, and disconnecting floodplains. Floodplain reduction tends to amplify flood peaks over a wider range of return periods, while retention basins and reservoirs reduce selected target events by temporarily storing water and delaying the flood wave.

In relation to reservoirs specifically, Austrian evidence confirms two principal functions. First, reservoirs can attenuate floods by storing part of the incoming hydrograph and releasing it more gradually. This effect is strongest directly downstream and depends on available storage volume, discharge structure, spillway configuration, and event duration. Second, reservoirs can support low-flow periods by releasing water to maintain ecological discharges, supply urban or industrial water uses, or compensate for seasonal shortages.

Studies cited in the Austrian section show that direct downstream flood peak reduction can be substantial downstream, near the structure, with average attenuation in some Alpine reservoirs ranging roughly from one-quarter to over one-third depending on event size. However, the attenuation effect is not linear and may even become negligible or locally adverse for certain small or very large events. For some small events the operation can badly influence the flood peak reduction. This is particularly relevant for LAREDAR, because it confirms that flood mitigation by reservoirs is event-specific and strongly conditioned by reservoir operation rather than storage volume alone.

The Austrian evidence also underlines the importance of downstream propagation. Flood peak reduction observed immediately below a dam decreases as the wave travels downstream and merges with tributary inflows. For future modelling, this implies that LAREDAR should distinguish between local attenuation effects and basin-scale relevance. Reservoir operation can be highly effective at local or sub-basin scales, but transboundary significance depends on whether the modified hydrograph remains detectable further downstream.

7.2. Hungary

Hungary's hydrogeographical setting makes reservoirs and lakes strategically important for both flood and drought management. The country's lowland character, transboundary river dependence, and exposure to both excess water and water scarcity create a setting in which storage systems serve multiple and sometimes competing purposes.

Reservoirs in Hungary fulfil a broad range of functions, including flood protection, drinking-water supply, irrigation, fisheries, recreation, tourism, and ecological water management. A distinction must be made between permanent multipurpose reservoirs and dedicated flood peak reduction reservoirs. The latter, such as Hanyi–Tiszasülyi, Tiszaroffi, or Cigándi, are designed to remain dry under normal conditions and are activated only at critical water levels, whereas reservoirs such as Lake Tisza perform continuous regulatory functions.

Lake Tisza is the most significant Hungarian example in terms of potential transboundary relevance. Created by the Kisköre Barrage, it affects the Middle Tisza system and therefore has hydrological relevance for upstream countries such as Romania, Ukraine, and Slovakia, and for downstream Serbia. Its main transboundary effects are linked less to direct flood peak reduction and more to flow regulation, timing, sediment retention, and low-flow support. During low-water periods, impoundment influences downstream discharge and water availability, while during flood periods the barrage may slightly alter wave timing rather than substantially reducing flood magnitude.

Hungary also emphasizes that barrages along the Tisza act differently from conventional reservoirs. They retain water within the river corridor and may influence the travel time of flood waves, potentially providing downstream countries with additional preparation time for flood defense. Conversely, during droughts and low-water periods, barrages can exert upstream influence through backwater effects. The example of the Novi Bečej dam in Serbia, whose influence extended far upstream during the 2022 drought, illustrates the importance of bilateral and multilateral coordination in heavily regulated river systems.

A central Hungarian conclusion is that individual reservoirs often have only local effects, but coordinated systems can generate basin-scale benefits. When reservoirs, barrages, and flood retention basins are operated as an integrated network, their influence becomes more significant and may extend across borders. This is particularly important for future modelling in LAREDAR. The project should therefore assess not only the role of individual structures, but also the cumulative effect of regulated and unregulated lakes, reservoirs, and retention areas acting together within a coordinated system.

Hungary also stresses the need to distinguish between active and passive systems. Regulated reservoirs offer direct and flexible management options, especially for extreme events, while unregulated lakes and natural water bodies function more as passive buffers. Both categories are relevant, but their hydrological effectiveness and governance implications differ significantly.

7.3. Slovenia

The Slovenian section demonstrates that transboundary effects are particularly relevant where lakes and reservoirs are embedded in larger regulated river systems such as the Sava and Drava. In these cases, even structures located outside the Danube main stem can have a significant downstream impact because they modify hydrological conditions in tributaries that ultimately contribute to the Danube system.

The Brežice reservoir on the lower Sava exemplifies a strongly managed hydropower reservoir with a clear flood-risk reduction role. Its operation integrates hydraulic, geomorphological, and anthropogenic factors, and because the Sava is a major Danube tributary, any regulation at Brežice may propagate downstream beyond Slovenia. In this sense, the flood-mitigation function of the reservoir is inherently transboundary.

An even more explicit cross-border example is Lake Ormož, created by the Varaždin hydropower system on the Drava. The reservoir extends across the Croatian–Slovenian border and serves multiple purposes, including flood and erosion control, support for gravity drainage and irrigation, and influence on groundwater recharge in the shared alluvial system. This illustrates that transboundary effects are not limited to river discharge alone. Reservoirs may also modify groundwater conditions, recharge patterns, and sediment transport across borders.

The Slovenian material further points to the cumulative importance of cascades. The chain of hydropower developments on the Drava in Austria, Slovenia, and Croatia has altered downstream water levels, discharge patterns, and sediment regimes. Such cascade effects are especially relevant for LAREDAR because they show that the transboundary influence of a single reservoir may be inseparable from the cumulative impact of the whole regulated system.

Finally, Slovenia highlights the role of basin-wide data integration. Reservoir inflows and outflows are part of the shared information base of the Sava Flood Forecasting and Warning System. This underlines an important lesson for LAREDAR: transboundary effects are not only hydrological, but also institutional and informational. Reservoirs contribute to transboundary forecasting and early warning not merely through physical storage, but also through the provision of operational data into shared basin systems.

7.4. Ukraine

The Ukrainian contribution indicates that, within the Tisza, Prut, and Siret sub-basins located in Ukraine, the role of lakes and reservoirs in modifying main-stem transboundary hydrology is generally limited. This is primarily because the systems are characterized by mountain runoff, rapid flood formation, and the absence of large channel reservoirs capable of significantly transforming the flood regime at basin scale.

In the Ukrainian part of the Tisza basin, the existing reservoirs are mainly small or medium-sized structures located on tributaries. Their functions include hydropower, fish farming, seasonal regulation, and local flood retention. The Vilshanske reservoir, associated with the Tereble-Rikska hydropower scheme, is the most important example, but even this structure has only a minor effect on overall Tisza runoff. Other reservoirs and ponds contribute mainly to local retention and modest attenuation of tributary flood peaks. Natural lakes, mostly of glacial origin, are too small to exert substantial control over basin-scale runoff.

A similar pattern is reported for the Prut and Siret sub-basins in Ukraine. Large reservoirs are largely absent, and the existing structures are small, often silted, and used mainly for local water supply, irrigation, fish farming, or seasonal storage. Their flood-control effect is weak and their influence on the main rivers is minimal. In these basins, natural floodplains, river regulation works, and levees remain more important than reservoirs for flood management.

The Ukrainian conclusion is therefore clear: current reservoirs and lakes in the Ukrainian pilot areas do not have a significant transboundary effect on downstream countries in terms of flood transformation. Their hydrological impact is predominantly local. Nevertheless, they remain relevant for LAREDAR because they illustrate a different type of pilot context: basins where extreme hydrology is governed more by topography, rainfall intensity, and rapid runoff than by major infrastructure.

At the same time, Ukraine notes that climate change may increase the relevance of integrated management in the future. More intense rainfall, more frequent droughts, and increasing variability may strengthen the need for modernization of existing structures, restoration of floodplains, and the use of nature-based solutions rather than reliance on large storage alone.

7.5. Scoping conclusions for future modelling

The results of the third questionnaire indicate that lakes and reservoirs across the pilot areas perform four main categories of hydrological function relevant to LAREDAR: flood peak attenuation, low-flow support, sediment and flow regulation, and system coordination within transboundary river networks.

Their effectiveness depends on a limited set of key factors: storage volume, outlet and spillway capacity, operating rules, event volumes, event duration, and position within the basin. Reservoirs tend to have their strongest impact immediately downstream, while transboundary significance depends on whether attenuation or release signals remain hydrologically visible further along the river network. In highly regulated cascades, cumulative effects may be more significant than the role of any single structure.

The country cases also show that transboundary effects take several forms. These include direct modification of flood hydrographs, changes in low-flow availability, backwater effects, sediment retention, groundwater recharge impacts, and contributions to shared forecasting systems. In some basins, these effects are clearly detectable across borders.

In others, such as the Ukrainian pilot basins, effects are mainly local and operationally modest.

For future modelling, the chapter suggests several priorities. First, LAREDAR should distinguish between local hydraulic effects and basin-scale transboundary relevance. Second, modelling should capture both active operational regulation and passive retention functions. Third, cascade effects and floodplain interactions should be explicitly included where relevant. Fourth, drought and low-flow support should be assessed alongside flood attenuation, because many structures serve both purposes.

Overall, the findings confirm that lakes and reservoirs are potentially important but highly differentiated components of transboundary hydrological management in the Danube basin. Their role cannot be generalized across all pilot areas. Instead, LAREDAR should adopt a typology- and function-based modelling approach that reflects the diversity of structures, operating regimes, and basin contexts represented in the project.

Key findings / Conclusion

This scoping study provides a comprehensive overview of the roles, characteristics, and management frameworks of lakes and reservoirs within the Danube River Basin (DRB), with a particular focus on their relevance for flood risk management and their potential transboundary impacts. The study was developed within the framework of the LAREDAR project to support the development of a harmonized approach for assessing and integrating lakes and reservoirs into basin-wide flood risk management strategies.

The analysis confirms that the Danube River Basin represents a complex hydrological systems in Europe, extending across diverse climatic, geomorphological, and socio-economic regions. The basin includes Alpine headwaters, lowland floodplains, and deltaic environments, which together generate highly variable hydrological conditions and diverse flood regimes. Hydrological extremes including floods and droughts are strongly influenced by precipitation patterns, snowmelt processes, basin morphology, and the synchronization of tributary flood waves. These characteristics create a strong upstream–downstream dependency across the basin and highlight the inherently transboundary nature of water management in the region.

Historically, the Danube Basin has experienced numerous significant flood events that have shaped modern flood protection policies and infrastructure development. Major floods such as those in 2002, 2006, 2010, and 2013 demonstrated the scale and transboundary character of flood risks in the basin. These events caused widespread damage across several countries and emphasized the importance of coordinated forecasting, reservoir operation, and integrated flood risk management approaches.

Within this context, lakes and reservoirs play a fundamental role in the hydrological functioning of the basin. Natural lakes contribute to flood attenuation by providing passive water storage during high-flow events, while artificial reservoirs allow controlled water retention and release through operational management. Their functions extend beyond flood mitigation to include water supply, hydropower generation, irrigation, ecological flow regulation, navigation support, and recreation. As multi-purpose infrastructure elements, reservoirs must therefore be managed in a way that balances flood protection with other competing water management objectives.

A key outcome of the study is the importance of distinguishing between different categories of lakes and reservoirs based on their hydrological characteristics and operational control. The classification developed within this study differentiates between natural lakes, managed lakes, river reservoirs, retention basins, and natural retention areas such as floodplains and wetlands. These categories differ significantly in their capacity to influence flood dynamics. Regulated reservoirs and actively managed hydraulic structures can provide flood mitigation by controlling discharge and storage volumes. In contrast, natural lakes and wetlands typically function as passive retention systems that attenuate flood peaks through natural storage processes.

The study also highlights that individual reservoirs generally exert their strongest impacts at the local scale. However, when considered as part of a coordinated network of water retention structures, their combined effects can influence flood propagation at the basin scale. Coordinated reservoir operation therefore represents a key mechanism for improving flood mitigation and reducing downstream flood risks across national borders.

An important focus of this work is the identification of transboundary effects associated with lakes and reservoirs. Many reservoirs within the Danube Basin are located on rivers that cross national borders or influence downstream countries through shared hydrological systems. The operation of these reservoirs may affect flood peak timing, discharge volumes, sediment transport, ecological conditions, and water availability in neighboring states. Consequently, reservoir management requires coordinated governance frameworks, transparent information exchange, and harmonized operational approaches among countries sharing the basin.

The study also demonstrates the importance of strong institutional cooperation and multi-level governance structures in water management. Across the Danube Basin, water management authorities, environmental agencies, hydropower operators, civil protection organizations, and scientific institutions all contribute to the planning and operation of reservoirs and flood protection systems. This multi-actor environment highlights the need for effective communication mechanisms and integrated decision-making frameworks that connect technical operators with policy and regulatory institutions.

Another important contribution of this scoping study is the identification of existing methodological approaches and data sources used by different countries in the basin. The analysis revealed significant variations in terminology, classification systems, operational rules, and available datasets related to lakes and reservoirs. These differences highlight the need for harmonized definitions, standardized data collection methods, and shared analytical frameworks in order to enable effective transboundary cooperation and comparable assessments.

To address these challenges, the study proposes the development of a common conceptual and methodological framework for evaluating the flood management roles of lakes and reservoirs. Such a framework will serve as the foundation for the **LAREDAR Harmonization Platform**, which aims to integrate relevant datasets within a joint GIS-based system linked to the ICPDR framework. This platform will support improved data sharing, coordinated reservoir management, and enhanced decision-making processes across the Danube Basin.

The review of operational frameworks across the Danube River Basin indicates that many reservoirs are managed as multipurpose systems balancing flood protection, hydropower generation, navigation, ecological requirements, irrigation, and water supply objectives. While this integrated approach provides flexibility under normal hydrological conditions, increasing climate variability and the growing frequency of prolonged droughts require a clearer prioritization framework for extreme water scarcity situations.

The LAREDAR project therefore recommends that, during officially declared drought or severe water scarcity periods, water management objectives should take precedence over energy production and other non-essential operational purposes. In such circumstances, reservoir operation should primarily aim to safeguard strategic water resources, maintain ecological flows, secure drinking water supplies, support critical agricultural water demands, and preserve minimum environmental conditions necessary for ecosystem resilience.

This recommendation reflects the increasing recognition that water security is becoming a critical component of climate adaptation and societal resilience within the Danube River Basin. Hydropower production remains an important renewable energy source; however, under exceptional drought conditions, reservoir operation should be guided by basin-scale water management priorities rather than energy optimization objectives alone.

To support this approach, future reservoir operating rules should incorporate drought-specific operational protocols, clearly defined priority hierarchies among competing water uses, and coordinated transboundary decision-making mechanisms. Such measures would strengthen the resilience of the Danube River Basin to future climate extremes while ensuring that limited water resources are allocated according to their highest societal and environmental value.

In periods of severe drought, water should be recognized as a strategic resource of overriding public interest, and reservoir operation should be adjusted accordingly across all sectors and administrative levels.

Finally, the study highlights the importance of integrating natural retention measures with artificial storage infrastructure. Floodplains, wetlands, and other natural retention areas play a complementary role to reservoirs by providing additional storage capacity and ecosystem-based flood mitigation benefits. The combination of natural and engineered solutions is increasingly recognized as a key element of resilient and sustainable flood risk management strategies in large river basins.

In line with European policy frameworks, the findings of this study support the objectives of the EU Floods Directive, which emphasizes the importance of coordinated flood risk assessment and management across international river basins. The study also aligns with the strategic goals of the International Commission for the Protection of the Danube River (ICPDR) and the EU Strategy for the Danube Region, particularly in strengthening transnational cooperation and improving integrated water management practices across the basin.

In conclusion, lakes and reservoirs represent critical components of integrated flood risk management in the Danube River Basin. Their effective use requires not only technical optimization but also strong transboundary cooperation, harmonized data systems, and coordinated operational strategies. The results of this scoping study provide an important knowledge base for the next phases of the LAREDAR project, supporting the development of the Harmonization Platform and contributing to improved basin-wide flood resilience in line with European water management policies.

Key Findings of the Scoping Study

- The **Danube River Basin (DRB)** represents one of the most complex transboundary hydrological systems in Europe, characterized by diverse climatic zones, high-value biodiversity status, geomorphological conditions, and hydrological regimes extending from Alpine headwaters to lowland floodplains and the Danube Delta.
- **Flood risks in the basin are strongly transboundary**, as hydrological processes and flood waves propagate across multiple countries. This creates strong upstream–downstream interdependencies and requires coordinated flood risk management among Danube countries.
- Several **major historical flood events** (notably in 2002, 2006, 2010, and 2013) have demonstrated the scale and impact of extreme hydrological events in the basin, highlighting the importance of basin-wide cooperation, improved forecasting, and integrated flood risk management strategies.
- **Lakes and reservoirs play a crucial role in flood risk management**, acting as water retention elements that can attenuate flood peaks, regulate river discharge, and support controlled water release during extreme hydrological events.
- **Natural lakes provide provide retention capacity for flood attenuation**, storing excess water temporarily during high-flow conditions, while **artificial reservoirs allow active flood management** through controlled operational rules and storage regulation.

- Lakes and reservoirs often serve **multiple purposes**, including hydropower generation, water supply, irrigation, navigation support, ecological flow maintenance, and recreation. Flood protection must therefore be balanced with other water management objectives.

- The **combined operation of multiple reservoirs within a river basin can significantly influence flood propagation**, demonstrating the importance of coordinated reservoir management at the basin scale rather than isolated local operation.

- **Transboundary impacts of reservoirs and lakes are significant**, as reservoir operation in upstream countries may influence downstream flood peak timing, discharge volumes, sediment transport, ecological conditions, and water availability.

- Effective management of lakes and reservoirs therefore requires **coordinated governance, transparent data exchange, and harmonized operational approaches** among countries sharing the river basin.

- The study identifies **considerable differences in terminology, classification systems, operational rules, and available datasets** across countries in the Danube Basin, which currently limit the comparability of analyses and the efficiency of transboundary cooperation.

- A **harmonized classification framework** for lakes, reservoirs, and retention areas is necessary in order to enable consistent assessment of their roles in flood risk management across the basin.

- **Natural retention areas**, including floodplains and wetlands, complement reservoirs by providing additional storage capacity and nature-based flood mitigation benefits, highlighting the importance of integrating natural and artificial retention solutions.

- The study confirms the need for **improved basin-wide data integration and analytical tools**, including shared GIS platforms and harmonized datasets that support cross-border analysis and decision-making.

- The results of this scoping study provide the **methodological and knowledge foundation for the LAREDAR Harmonization Platform**, which aims to support coordinated assessment and management of lakes and reservoirs across the Danube River Basin.

- Overall, the findings underline that **effective flood risk management in the Danube Basin depends on integrated approaches combining technical infrastructure,**

natural retention measures, transboundary cooperation, and harmonized data systems, in line with European flood risk management policies.

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Annexes

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Catalogue of basic definitions summary.p

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