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CIMA Research Foundation (Pilot 4)

Eurac Research (Pilot 5)

Contents

Introduction

The scope of this deliverable is to the status quo at the pilots, including local needs and legislation on water management. A-DROP includes five pilots, all focusing on various aspects of drought monitoring and management:

- Improvement of the National Drought Watch Tool (NDWT) and National Irrigation Support Tool (NIST) in Slovenia (Pilot 1)
- Development of a climate service to evaluate water requirements for snowmaking and the capacity to produce snow in the future at Alpine ski resorts (Pilot 2)
- Generation of a tool to simulate the Upper Isar hydropower complex under drought conditions, using O11 data for model calibration (Pilot 3)
- Development of a drought-risk assessment dashboard for water governance and hindcast testing of a hydrological forecast model in Valle d'Aosta (Pilot 4)
- Set up and hindcast testing of a machine learning (ML) based hydrological forecast model for the Adige catchment (Pilot 5)

For each Pilot, we elaborate on the study area, the current legislation on water management, current practice and stakeholder needs, and the pilot development plan (including risks).

1 Pilot1: Improvement of the National Drought Watch Tool (NDWT) and National Irrigation Support Tool (NIST) in Slovenia Study area

Pilot 1 in Slovenia has two study areas to provide the best quality existing ground-truth soil moisture data as possible for the validation of the satellite products during the lifetime of the A-DROP project. Study area 1 in Pilot 1 is located in central Slovenia (longer ground-truth data series, calibrated proximity soil moisture data, from March 2024 on), while Study site 2 of the Pilot 2 is located at Dobrovce (providing uncalibrated proximity soil moisture data, from February 2025 on).

1.1 Study area 1 in Pilot 1: Ljubljana

The first study area of Pilot 1 is located at the experimental field of the Biotechnical Faculty, University of Ljubljana, in Ljubljana (46°02'58.4"N, 14°28'15.7"E). The flat area is characterized by mosaic agricultural land use (arable fields, grasslands, forest, field paths) and urban elements (buildings, sheds, paved surfaces). A regulated channel of the Glinščica stream flows along the northern edge of the field. Soils in the sensor's measurement area are heterogeneous. According to the World Reference Base for Soil Resources [1], they are classified as Eutric or Mollic Gleysols. According to the Slovenian soil classification [2], they are described as pseudo-gleyed or hypo-gleyed eutric brown soils, indicating water stagnation—mainly from precipitation (due to heavy texture and higher soil density) and occasionally groundwater.

The area was previously drained for the construction of a drainage system. The saturated zone in the soil lies at a depth of 1.2 to 1.5 meters (Glinščica water level). The average long-term air temperature from 1981–2010 was 10.9 °C, and the average annual precipitation was 1362 mm [3]. The field has mixed land use. Arable crops (wheat, corn) and permanent grasslands are predominant. At the area, there is an existing cosmic ray neutron sensor (CRNS) installed at 2 meters and 18 volumetric capacitance sensors at soil depths 10 and 20 cm. Buildings are also partially included within a 200-meter radius of the CRNS (Figure 1).

Figure 1: Calibration grid of the neutron detection sensor (Land use data source: MKGP, 2024)

1.2 Study area 2 in Pilot 1: Podravska region, Dravsko polje, Dobrovce village

The second Slovenian area is located in the Podravska Statistical Region (Slovene: Podravska regija or Podravje). The region is an alluvial plain of the river Drava, in north-eastern Slovenia. Dravsko polje is an alluvial plain of the river Drava, in north-eastern Slovenia. As water is resource of national importance is on general regulated by the state as is in the case of Dravsko polje study area with two decrees on water protection zones (WPZ).

The Cosmic Ray Neutron Sensor is located in the village of Dobrovce at Dravsko polje (46.482036, 15.704108), which is in the most restrictive water protection zone, immediately surrounding the intake or aquifer. The approximate altitude of the area is 250 meters above sea level, with an average land slope of 1 %. The soil type is dystric brown soil on non-carbonate sandy-gravel sediments, soil type no. 75-53 [4]. The soil depth is shallow (60 %) to moderately deep (40 %). Maribor Airport is a representative meteorological station for this area. It is the only station in Podravska statistical region with a sufficiently long data record (more than 30 years). Data from this station is used to evaluate drought impact for this region and compare it to new developing methods (CRNS). The average temperature for the last 30 years for this area is 10.7 °C [3]. The deviation from the average temperature shows a linear increasing trend of 0.32 °C. On average, around 900-1000 mm of precipitation falls annually in the Drava river basin (1991-2010). Main sources of the groundwater body are infiltration of precipitation, sinking streams from Pohorje Massif in NW, Drava river in the N, and Polskava river in the SW of the aquifer. Due to the soil type and climate change (rapidly developing summer droughts ("flash droughts") during heatwaves), the area is very prone for agricultural drought. Seven major droughts (proclaimed natural disaster) were reported in the last 20 years, the last recorded in 2022 [5].

Intensive agriculture is spread in the area of Dravsko polje, with several restrictions in management practices due to drinking water protection. The droughts severely impact the area, thus farmers are highly advised to use combinations of precise irrigation and Nature-Based Solutions (NBS, like mulch-till, crop rotation/change, greening) to adapt agriculture to climate change. This is why feasibility studies to enhance monitoring networks and integrate high-resolution climate and satellite data (OI11 and OI12) for improved National Drought Watch Tool (NDWT) and National Irrigation Support Tool (NIST) in Slovenia are needed.

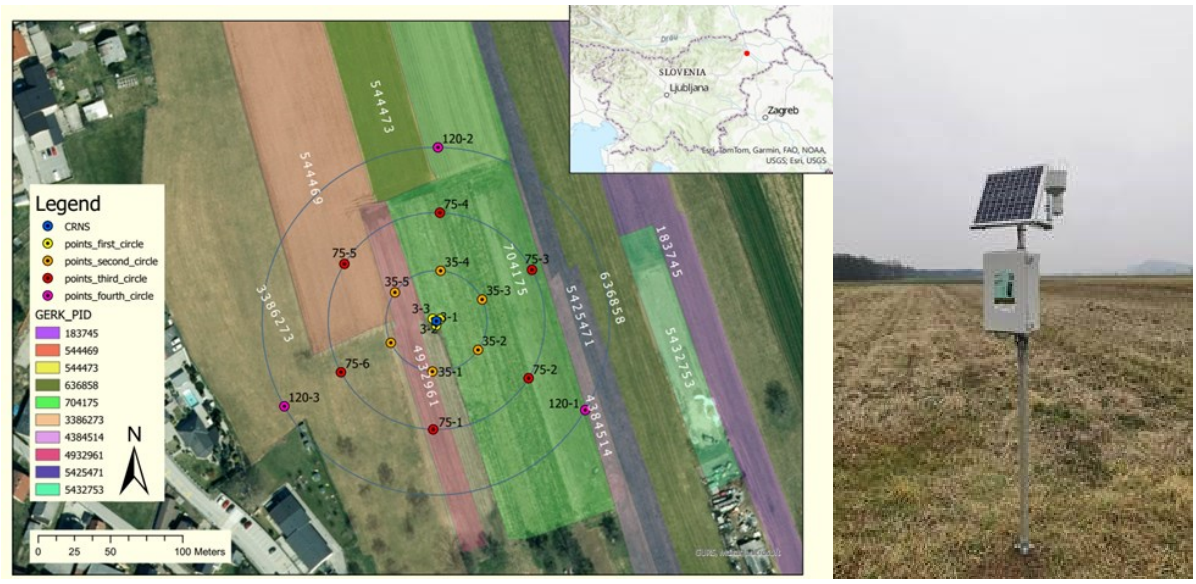

Figure 2: Calibration grid of the neutron detection sensor at are 2 Pilot 1, Dobrovce (Land use data source: MKGP, 2025).

CRNS at Dobrovce, Podravska region has been installed on 11th of February 2025. The probe has been connected to the FINAPP database and has been collecting data since the day of installation. The methodology for CRNS integration in the existing National drought watch tool is the same as it has already been described in the section 1.1.1 (study area 1, Ljubljana). The CRNS in study area 2 has undergone the first calibration and requires two more until the end of the year 2025.

The June 2025 have been extremely dry across all of Slovenia. Based on the 1991–2020 climatological period, this represents the **largest recorded water balance deficit** in the surface soil layer for this time of year in most regions.

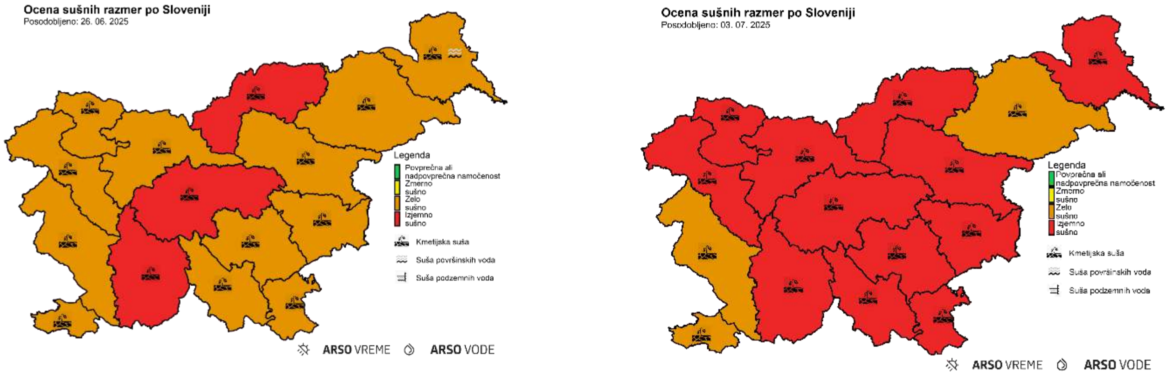

Figure 3: The national drought watch tool showed exceptionally dry conditions (red) in three statistical regions on 21th of June 2025 (left) and 3rd of July (right). The Podravska region was characterised as very dry. Agricultural drought was declared in all regions (ARSO, 26.6.2025).

1.3 Current legislation on water management

1.3.1 Core National Law

The EU Water Framework Directive was transposed into Slovenian legislation by the **Waters Act** [7], which among other objectives also targets good ecological and quantitative status of waters in Slovenia as well as reducing or eliminating pollution of waters by hazardous substances. The Slovenian Water Act [8] restricts the use of water by the instrument of water rights. The water right grants a right to use water at a time when there is enough water; otherwise, the water use is restricted. National River Basin Management Plan (RBMP) [8].

National Decree on Water Management Plans RBMPs [8] have been prepared for two river basin districts (RBDs) in Slovenia, North Adriatic RBD and Danube RBD. RBMPs for the two river basin districts include an overview of the state of the aquatic environment, the pressure and impacts of human activities on aquatic environment and the results of monitoring of status of waters. In the 3rd cycle of RBMP (2022-2027), drought is included as an important water management issue and related updated programme of measures is under preparation [8].

Two decrees on water protection zones (WPZ) are imposed on Drava river basin (Podravksa region). One for the northern (Decree on the water protection area for the aquifers of Ruše, Vrbanski plato, Limbuška dobrava and Dravsko polje and one for the southern part (Decree on the water protection area for the aquifers of Dravsko-ptujsko polje) [9,10].

Municipalities have also the right to enforce decrees on municipal water protection zones for small water resources of local importance. For the state decrees enforcement is responsible Ministry of Natural Resources and Spatial Planning (MNVP).

1.3.2 Agriculture and Water in Podravska Region

Although much water governance is national, the Podravska region lies within the Drava sub-basin of the Danube catchment, hence is subject to both national Waters Act and EU-derived frameworks.

National efforts under **Rural Development Programmes** 2014–2020 and 2023-2027 include targeted agri-environment-climate payments, ecological practices, and irrigation investments aligned with water protection goals [11]

Inside **water protection zones**, core zones (VVO I) ban the use of plant protection products (PPPs); wider zones impose tight restrictions and enforce buffer strips along water bodies (e.g. 5 m–15 m no-spray zones). Agricultural users must use **less harmful PPPs** if alternatives are available—especially those not on EU priority pollutant lists—and prioritize mechanical or biological measures over chemicals.

Regional policy (e.g. Regional Strategy for Circular Bioeconomy – Podravje 2030) [12] promotes integration of water reuse, biomass valorisation, and soil fertility improvements—enabling more sustainable agriculture under the water governance framework.

1.3.3 Climate Adaptation National Action Plan

The main cross-sectoral strategic document on adaptation is the Strategic Framework for Climate Change Adaptation, adopted by the Government in December 2016 [13]. The document foresees the monitoring of steps and methods of implementation by the Interdepartmental Working Group on Adaptation, which will produce regular biennial reports and periodic updating of the steps and directions of the guidelines. It is planned that the strategic document will be followed by an Action Plan of Measures for Adaptation. There are several other documents with adaptation goals and measures, such as the Forestry and Agriculture Development Strategies, which have their own set of policies aimed at promoting adaptation in their respective sectors.

Despite adopting a national CC adaptation framework in 2016, sectoral measures remained inadequate to accelerate policy implementation. The 2020 Integrated National Energy and Climate Plan [14] aimed to enhance resilience, but key actions, like a detailed adaptation plan by 2021, were not fully realized. In 2021, the Slovenian government set a goal of achieving net zero greenhouse gas emissions by 2050 with the Resolution on long-term national climate strategy. A government-funded program later proposed integrating vulnerability assessments into spatial and urban planning. However, shifting responsibility to municipal planning without harmonized frameworks has slowed progress, highlighting the need for a better facilitated approaches to local adaptation action.

The heatmap indicates the level at which different sectors are currently considering CC (Figure 4). Forestry seems to be more pro-active than other sectors. Agriculture shows partial consideration across categories under the Strategic programme of the Common Agricultural Policy [15], indicating some attention to CC, but with room for improvement. Sectors health, tourism, flood management, water supply and urban drainage need more attention to integrate climate considerations. Many sectors show partial efforts, indicating ongoing work but also areas where planning can be strengthened. Overall, the heatmap highlights disparities across sectors in terms of CC planning, suggesting priorities for improvement.

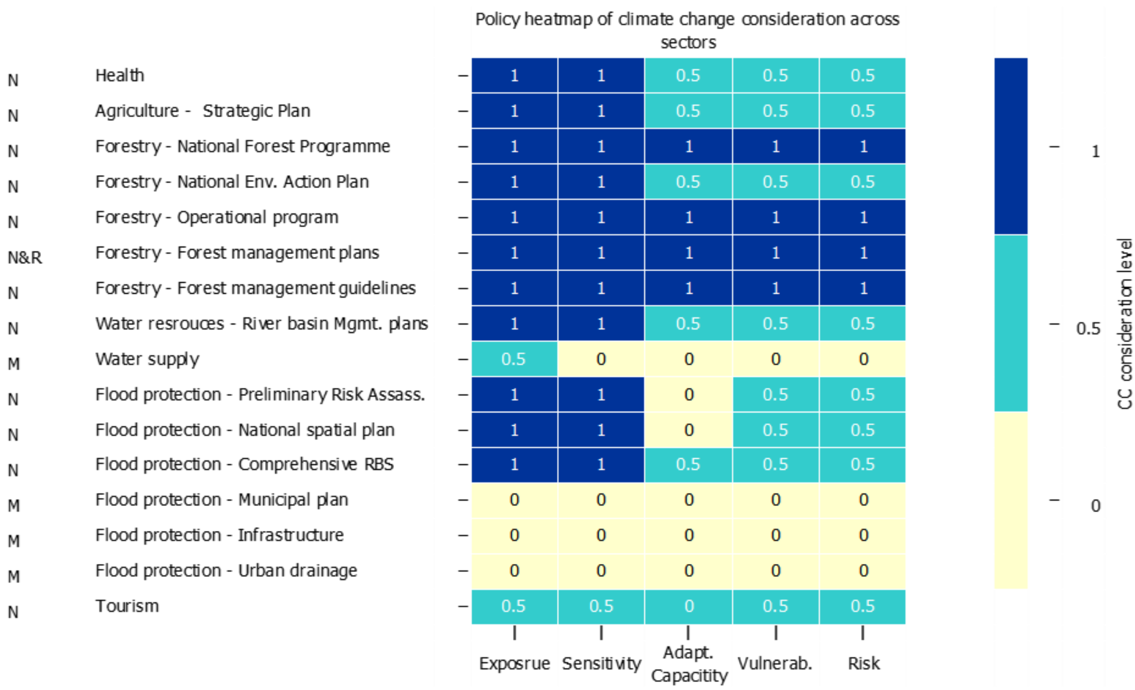

Figure 4: Heatmap of climate change consideration across sectors

1.3.4 The legislation addressing drought

In Slovenia, there is no legal umbrella document directly addressing drought and drought management. In various documents, drought is only considered indirectly and is included in them by reference to a natural disaster which is addressed through water permits and restrictions in case of low flows. The Acts that do mention drought include drought as a whole and do not differentiate between different types of drought (i.e. drought of topsoil level, of surface waters, or of groundwaters).

The main Acts in relation to drought are the Protection Against Natural and Other Disasters Act and the Natural Disaster Recovery Act [16,17]

National and Regional Drought Management Plan (DMP): Given that Slovenia recognises drought as a national issue, it is required by the UNCCD to develop a National Action Plan. In 2013, Slovenia laid the groundwork for this plan; however, as of 2025, a Drought Management Plan has not yet been established as a separate legally binding document.

Restrictions on water use during drought period are set in detail by **Decree on criteria for determination and on the mode of monitoring and reporting of ecologically acceptable flow** [18] and by Decree on the river basin management plan for the Danube Basin and the Adriatic Sea Basin [19]. The restrictions are supervised by the state inspection.

Decree on the river basin management plan for the Danube Basin and the Adriatic Sea Basin prohibits and restricts the excessive use of water, but according to Article 5, it is allowed to use of very small amount of water for irrigation, also when the actual flow at the point of water abstraction/diversion is lower than the determined EAF [19].

Resolution on the National Programme for Protection against Natural and Other Disasters 2024-2030. The program aims at achieving the general goal of protection against natural and other disasters which is to reduce the number of accidents and to prevent or mitigate their consequences in order to make life safer and more quality [16]

National Environment Protection Programme with programmes of measures until 2030. In the frame of the »Water regulation« the document recognises the **drought** as an issue with evident impacts and provides general directions for mitigating drought impacts [20]

Rural Development Programme of the Republic of Slovenia 2023–2027 (2022) (RDP) focuses mainly on three priorities: restoring, preserving and enhancing ecosystems related to agriculture and forestry; competitiveness of agri-sector and sustainable forestry; and social inclusion and local development in rural areas. **Drought-related problems** are addressed as priorities through aiming at improving biodiversity and status of water and soil [11].

Plan for the development of irrigation and water use for irrigation in agriculture by 2023 and a program of measures to implement the plan of development of irrigation and water use for irrigation in agriculture by 2023. No new plan from 2023 onwards has been prepared yet [21].

1.4 Current practice

Early warning system and related protocol of actions in Slovenia is not legally defined. The Slovenian Environment Agency assesses drought severity on the basis of its operational drought indices and provides the information to the public. In 2021, Sušomer tool - National Drought Watch Tool (NDWT) [22] is in place as the foundation for drought EWS. It is managed by ARSO and a bulletin is issued every Thursday.

- **Slovenian Environmental Agency (ARSO)** provides information/tools related to drought conditions to general public, farmers, relevant institutions involved in drought management and other interested stakeholders via platform National Drought Watch Tool [3, 21]
- The information is updated weekly and disseminated every Thursday;

The system provides information on meteorological conditions, drought status in topsoil (agrometeorological and agricultural ecosystems), surface water, and groundwater. It includes text, graphs, maps, and a combined map displaying all three types of drought, as well as predictions of trends for the following week.

The agrometeorological forecast online application [22] has the following functionalities:

- It provides agrometeorological variables in the current year (air temperatures and temperature sums, soil temperatures and condition, water balance, evapotranspiration and precipitation - automatic stations). Available also data for meteorological water balance, evapotranspiration and other variables for the last 5 days; long - term averages of agrometeorological variables in the period (1971-2000), archive of agrometeorological data (after 1961); and phenological development of plants.

- Information about drought conditions is also spread via social media as Facebook, Instragram and Twitter.

- In case of drought, ARSO informs about it through different media, like national TV, radio, newspapers.

Municipalities and drinking water suppliers inform public if measures on water-use restriction are in place (their websites). This usually means a ban on the use of drinking water from public water supply for watering gardens and irrigation in agriculture, washing cars, filling swimming pools and other uses.

Based on post-drought-oriented legislation on drought, drought management is carried out to avoid impacts of drought. **In case of extreme drought**, the Administration of the Republic of Slovenia for Civil Protection and Disaster Relief declares drought as a natural disaster. Only in case if drought reaches the extent of natural disaster in agriculture, there is a procedure of evaluating natural disaster damage costs and of compensation for damages to affected farmers.

1.5 Stakeholders needs

We identified the most pressing challenges in the field regarding the implementation and expansion of irrigation. We have formulated questionnaires for the farmers to determine what additional support they require for upgrading the irrigation forecasting system. In most parts of the country, there is a lack of real data on how many farms use various tools for drought and irrigation forecasting, the reasons why they do not adopt such tools, and what would help make the use of support tools more accessible and beneficial. We have identified farms from Pilot Area 1 and beyond, with whom we will conduct a workshop in the second reporting period. Other stakeholders, such as municipalities, irrigation system managers, and observer representatives, will also be invited to participate. We will also present the ADO platform to the participants (initial activity for A3.2). The workshop to get farmers needs is planned for beginning of September 2025.

1.6 Pilot development plan

In Pilot 1, the following activities are planned for the next reporting period, as in Table 1.

Table 1: time plan for Pilot 1

Tasks	RP3	RP4	RP5	RP6
	2025-2026	2026	2026-2027	2027
	sep - feb	mar -aug	sep- feb	mar - aug
Comparison between the auto-calibrated and calibrated CRNS measurements on Study site 1.				
Further calibrations of CRNS, Study area 2.				
The workshop activity 1.1.				
Test of the prepared methodology for Economic Analysis of the Justification of Irrigation Systems.				
Economic analysis for test farms.				
Comparison between the auto-calibrated and calibrated CRNS measurements, test area 2.				
Continuation of discussion on possible improvement of national drought watch tool and irrigation decision support tool with the Slovenian Environment Agency. Testing in real-life.				
Provision of meteorological data (Air temperature (2m height), Relative air humidity, Wind speed, Solar radiation) for calculating ETc and comparison of ETc determined from satellite products for both Pilot 1 locations.				
Provision of lysimeter-based ETc and comparison of ETc determined from satellite products, location 1 of Pilot 1.				
Validation of satellite products against ground-truth soil-moisture measurements.				

1.7 Risks and Challenges

Currently it is not clear if the use of the national irrigation decision support tool (SPON) will be possible, as the government has decided to shut it down in September 2025. We are in in discussion with the government whether there will still be a possibility to use the tool after September 2025. If that will not be possible, other existing tools will be used (e.g. IrriGEN).

Other potential risks:

Table 2: risk analysis for Pilot 1

Risk	Risk level	Mitigation
Introduction of CRNS soil moisture sensing into drought watch tool and irrigation decision support tool: data transition, fail of data connection, inexistence of tools	high	Appropriate data protocols for data transition. No power over shutting down of tools (related to irrigation), but alternative options have been already identified (local IrriGen, Finapp irrigation decision support system)
Products of WP1 unavailable	low	No power over this, the risk addressed in WP1
Remote sensing data might not be able to capture trends at a required scale over the pilot area and in time	low	Change the scale, adapt the validation protocol
Evaluating the satellite products with in-situ data (different soil moisture sensor – from point to proximity): fail of equipment	low	Regular check, replacement
Lack of correlation with in-situ data	low	Changing algorithm, changing scale

2 Pilot2: Development of a climate service to evaluate water requirements for snowmaking and the capacity to produce snow in the future at Alpine ski resorts

2.1 Study area

La Thuile is an Italian ski resort located in the Aosta Valley (Valle d'Aosta) in North-Western Italy. The ski resort is connected to its French neighbour, La Rosière, since 1984. Together, they form the San Bernardo ski area, which has 160 kilometres of linked ski pistes spanning Italy and France (Figure 5). The area is best known for the Petit Saint Bernard Pass, a border crossing at an altitude of 2,200 metres with views of Mont Blanc. The highest point in the area is Belvedere, which sits at an altitude of 2,600 metres. The majority of the slopes are classified as red or black, indicating a predominance of difficult or very difficult runs. In particular, the piste number 3 ("Berthod") is considered one of the steepest in the Alps (slope of about 76%). La Thuile regularly hosts winter sports competitions, for which the ski runs must be prepared specifically. For example, in March 2025, La Thuile hosted the Women's Ski World Cup for the third time. La Thuile is part of the Comunità Montana Valdigne Mont Blanc ("Valdigne Mont Blanc Mountain Community"). This area, which also includes a spa resort (Pré-Saint-Didier), welcomed 153,000 tourists during the winter of 2023-24.

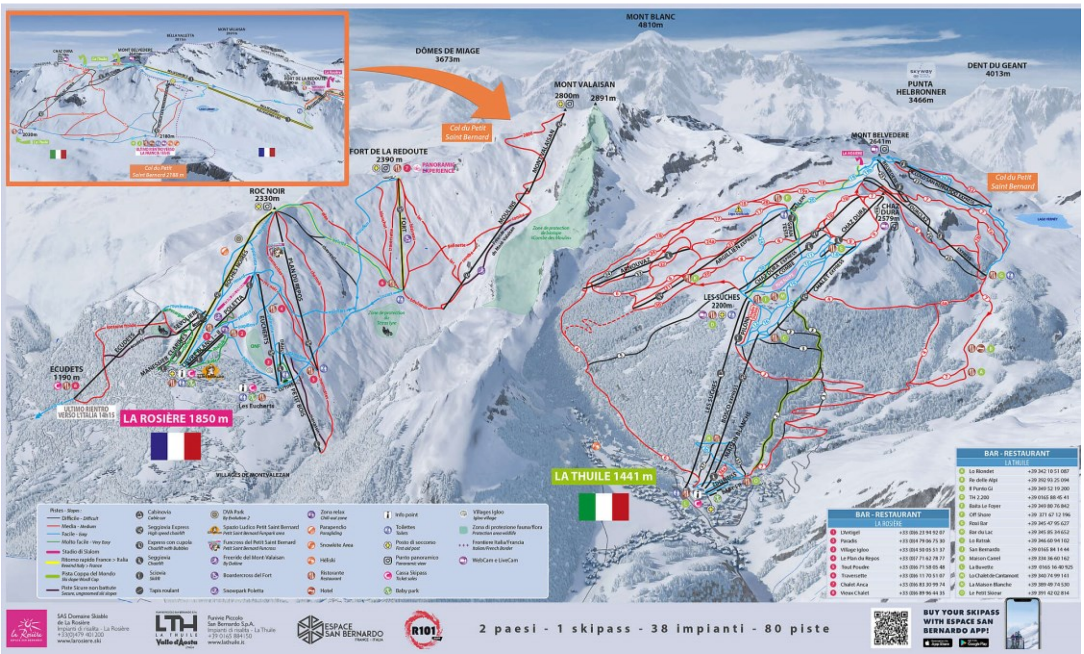

Figure 5: Official ski map of the San Bernardo ski area. La Thuile, on the Italian side, is connected with La Rosière, on the French side, through the Petit Saint Bernard Pass (shown in the top-left insert). (Source: Abest-Horizon, 2024.)

Avoriaz is a French ski resort located in the Haute-Savoie *Département*. Perched at 1,800 meters, it offers direct access to the vast "Portes du Soleil" ski area, one of the largest in the world, spreading between France and Switzerland (Figure 6). Known for its striking architecture that blends with the surrounding landscape, Avoriaz is a car-free, pedestrian-friendly resort. The resort is also celebrated for its commitment to its innovative approach to winter tourism. The average altitude of the ski lifts is 1,790 metres, with a minimum altitude of 970 metres, and the ski area offers a maximum vertical drop of 1,500 metres. The ski area has a fleet of ski lifts with a high-power moment: 18,800 person-km/h. The fleet is relatively young, with an average age of 24 years, and 39% of the ski lifts are less than 10 years old. Avoriaz is a major ski resort, recording 1,238,400 skier-days during the 2023–2024 [24] winter season, and generating €67 million in revenue from ski lift operations alone.

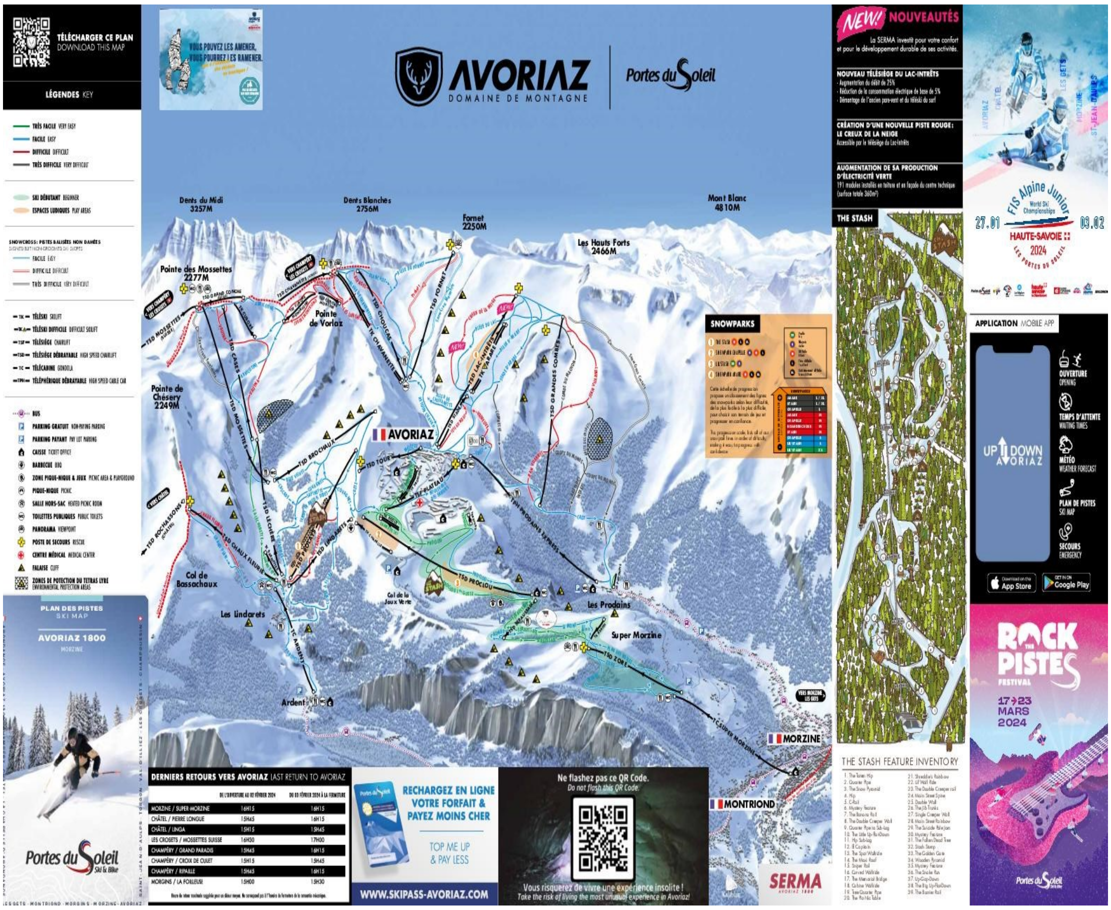

Figure 6: *Official ski map of Avoriaz ski resort. On the left, the connection to the "Portes du Soleil" ski area and the Swiss sector. On the right, the cable car reaching the nearby village of Morzine. (Source: Abest-Horizon, 2024)*

The Garmisch-Partenkirchen Zugspitze ski resort is situated in southern Germany, in the Bavarian Alps, and features two main ski areas: the Garmisch-Classic and the Zugspitze Glacier ski area. Zugspitze is Germany’s highest peak, reaching 2,962m.

Figure 7 shows that the Garmisch-Classic area offers ski slopes across three interconnected mountains: Hausberg (1,310 m), Kreuzeck (1,651 m), and Alpspitze (2,628 m). The ski area's elevation ranges from 740 m to 2,050 m. The area features the Kandahar downhill run, known for World Cup ski races. The Zugspitzplatt ski area, located between 2,000 m and 2,720 m altitude, offers reliable snow conditions throughout the season thanks to its high elevation and glacier. The Zugspitzplatt features 20 km of ski slopes, including 7 km of blue (easy) and 13 km of red (intermediate) pistes. Skiing is typically possible from early December to early May. On the small glacial plateau at Zugspitze began winter operations as early as mid-October and as late as mid-December in recent years.

Figure 7: Official ski map of Garmisch-Partenkirchen Zugspitze ski resort. On the left, the Garmisch-Classic ski area. On the right, the cable car reaching the Zugspitze ski area.

The three sites, like all ski resorts, have seen the duration and thickness of snow cover decrease, particularly below 2000 meters [25] Ski resorts have therefore invested in snowmaking systems to ensure the operation of their ski areas throughout the winter season. At La Thuile, part of the ski slopes is equipped with snowmaking systems, and the ski area includes an artificial reservoir with a storage capacity of 120,000 m³ to produce snow. Avoriaz also operates snowmaking systems, with 38% of its ski area covered by this equipment. The ski resort currently has three water reservoirs with a total capacity of 128,000 m³ and is building an additional 92,000 m³ reservoir. The Bayerische Zugspitzbahn – the ski lift operator of the Garmisch-Partenkirchen Zugspitze ski resort - has completely dispensed with snowmaking systems in the Zugspitze ski area and is concentrating snowmaking exclusively on the Garmisch-Classic ski area.

2.2 Current legislation on water management

The European Union's legal framework supports water legislation in its member States. Germany, France and Italy have transposed the Water Framework Directive (2000/60/EC) [26] into their national laws. Italy implemented it through Legislative Decree No. 152 of 2006, from its Environmental Code [27]. France incorporated it through the Law on Water and Aquatic Environments (LEMA), which the government enacted on 30 December 2006 [28]. In Germany, the Federal Water Act (Wasserhaushaltsgesetz) [29] have been amending to consider legal implementation of the Water Framework Directive from the UE.

In the French Alps, most water use restrictions are implemented at the Département level—[30] corresponding to the NUTS-3 administrative scale—in coordination with the Rhône, Méditerranée, Corse Water Basin Agency. The *préfet*, as the State's representative, can classify drought risk on a four-tier scale: vigilance, alert, reinforced alert, and crisis. Water abstraction limits are defined by *prefectoral decree* following consultation and are applied within designated management zones. These zones correspond either to surface water catchment areas or to groundwater bodies, such as aquifers or portions of aquifers. The Avoriaz ski resort, located in the Haute-Savoie *département*, falls within the "Arve Amont" management zone—one of nine such zones defined within Haute-Savoie. Departmental drought decrees may implement restrictions on water withdrawal that might impact snowmaking management. This is particularly the case when autumn or winter water flows are low. The withdrawals subject to the restrictions may be those made directly from the natural environment, or those taken from the drinking water networks, to give priority to this use when the resource is scarce. Specific proposals and recommendations have been made in 2022 by the public authorities ("Inspection Genérale de l'Environnement et du Développement Durable" report). According to a national report [31], the direct impact of the 2022 drought across France is estimated at €5.1 billion. It is likely that the total cost is underestimated, as certain impacts, such as those related to the tourism sector, have not been included in the estimate. This drought led to legislative changes, including improved compensation for damage to property [32] caused by clay shrinkage and swelling. However, these legislative changes do not directly concern mountain tourist areas.

In Italy, a similar framework to deal with water management has been set up. Considering recent droughts and their intensification, the government has introduced a new regulatory tool: Decree-Law no. 39 of 2023 (Drought Decree) [33]. This focuses on the urgent need to improve national water resilience. These regulations streamline the authorisation process, particularly for the design and construction of hydraulic infrastructures and rainwater reservoirs. This focuses on the urgent need to improve national water resilience. These regulations streamline the authorisation process, particularly for the design and construction of hydraulic infrastructures and rainwater reservoirs.

Germany's water management is primarily governed by the Federal Water Resources Act (WHG) [34], with implementation carried out through state-level legislation, including the Bavarian Water Act (BayWG) [35]. The town's drinking water is primarily sourced from groundwater wells located in nearby Grainau**.** These wells lie within protected drinking water zones [35] to ensure water quality. According to the Federal Water Resources Act (WHG) [34], the priority is to supply water from local sources wherever possible. The strategies include the legal prioritization of drinking water [35] over industrial or agricultural use when resources are limited over industrial or agricultural use when resources are limited.

2.3 Current practice

There is a wide range of water sources employed for snowmaking. The water may be drawn from the natural environment, from a drinking water network when overflow occurs, or from a hydroelectric facility. Since the early 2000s, ski area operators have been constructing high-altitude water reservoirs to support snowmaking. These water reservoirs are designed to store water and ensure its availability when meteorological conditions are suitable for snowmaking, especially during winter season when mountain rivers have their lowest flow rate. According to an environmental administration report, [37] approximately 50% of the water used for snowmaking in France passes through water reservoirs, which are mainly filled by withdrawals from the natural environment. It passes through water reservoirs, which are mainly filled by withdrawals from the natural environment.

Two pilot areas (La Thuile and Avoriaz) have equipped their ski areas with high-altitude water reservoirs to have a supply of water to produce snow. The La Thuile ski area is equipped with an artificial water reservoir located at Gran Testa, at an altitude of 2,300 metres, with a storage capacity of 120,000 m³ [38]. This reservoir supports a snowmaking network that covers 26% of the ski area — equivalent to 40 km out of 150 km of ski runs. Avoriaz ski resort has a network of water reservoirs. The largest of these, with a capacity of 80,000 m³, was commissioned in 2013 and is complemented by two smaller reservoirs with capacities of 44,000 m³ and 4,000 m³ respectively. Figure 8 highlights that the ski resort operator is currently building an additional water reservoir with a capacity of 92,000 m³. This latest water reservoir will ensure the snow reliability in a crucial sector of the resort's ski area, located at lower elevation and ensuring the connection with the neighbouring resort of Morzine. According to a study report simulating pumping in Lake 1730 in Avoriaz to supply the future reservoir, the drought-stricken year of 2022 saw zero availability between June and December. Depending on the intensity of the drought, reservoirs may not fill up as expected. Consequently, their storage capacity for the winter tourism season is no longer guaranteed. Depending on the intensity of the drought, reservoirs may not fill up as expected. Consequently, their storage capacity for the winter tourism season is no longer guaranteed.

The Zugspitze ski area in Germany has no snowmaking facilities. [39] The Garmisch-Classic ski area has more than 200 snow cannons covering about 62% of the ski slopes [40]. The water used for snowmaking comes from two reservoirs that are filled with rainwater and natural spring water during the summer months.

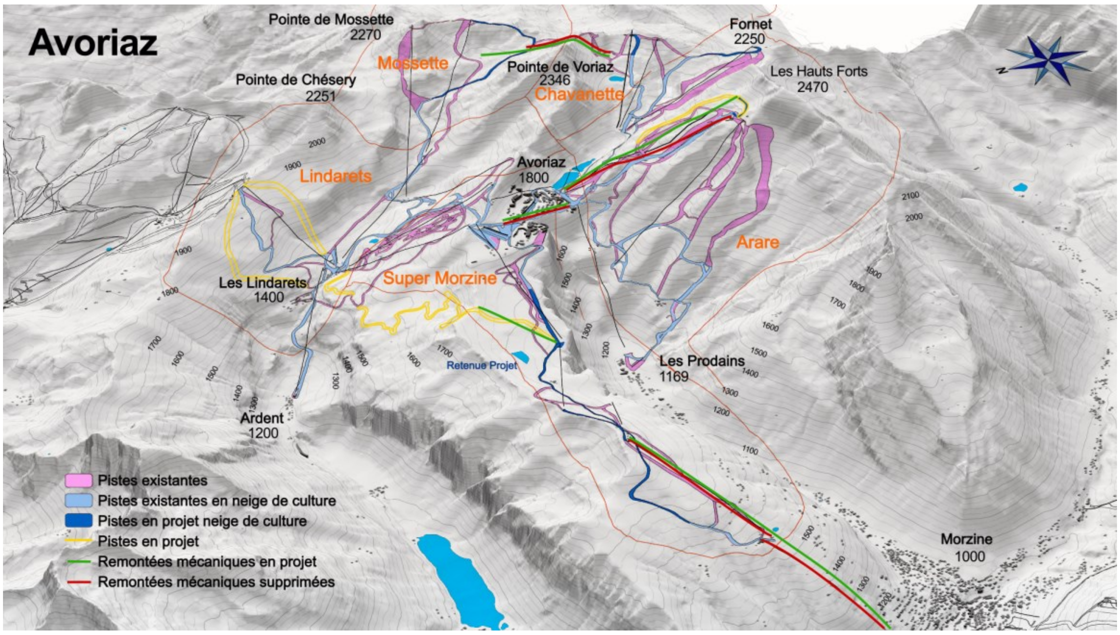

Figure 8: Current equipments and future projects at Avoriaz ski resort. In red the lifts that will be removed and in green the ones that will be added. Existing slopes are represented in pink, in light blue if already equipped with snowmaking and in dark blue if they will be equipped in the coming years. New slopes are in yellow. In the middle of the image, the water reservoir that is currently being built (”retenue projet”).

Tourism operators are facing growing tension over the sharing of water resources. In addition, the presence of media and reputational pressures can influence the desirability of a tourist destination. In response, the ski tourism industry is implementing measures to enhance the efficiency and moderation of water consumption and usage.

The pilot ski resorts have implemented complementary strategies for the sustainable management of their water resources. Since 2016, the snowmaking infrastructure at La Thuile in Italy is also used to generate hydroelectric power [41]. Water circulating through the system drives turbines, producing electricity that is fed into the Italian grid via the Compagnia Valdostana delle Acque (CVA – Water Company of Aosta Valley). Avoriaz in France has a swimming pool and a golf course. The resort has measures in place to make the most of water resources [42]. Since 2022, the swimming pool has been recovering an average of 25 cubic metres of water per day. The water is stored temporarily to allow the chlorine to evaporate, making it reusable. Tanks have been put in at various places at the resort to collect rainwater: 2,000 litres are collected at the swimming pool, 4,000 litres at the golf course, and 3,000 litres by the resort's services. In Germany, a turbine was installed in the Garmisch-Classic area in

2024 that employs the use of overflow water from water storage basins to generate electricity. Zugspitze site was one of the pilot ski resorts for the creation and development of a weather forecasting and snow management system [43]. The purpose of the system was to improve forecasting capabilities over different time scales, ranging from a few days to several months (see 2017-2020 PROSNOW® project) [44].

2.4 Stakeholders needs

Preparatory workshops for the project have been held in March 2025 with the heads of the three ski resorts. Several elements of knowledge regarding the state of water resources in the case study areas have been compiled. Spatial data on the location of ski runs and the snow production network were collected for modelling purposes. In addition, a range of key indicators were collected from ski area operators, including temperature, snow depth, precipitation and water flow measurements. Ski lift operators such as Avoriaz have already carried out hydrological studies and collected data from the instrumentation of existing water structures in the ski resorts.

For several years now, ski resorts have been investing in systems and tools to enhance their snowmaking management. In addition to these improvements, they are conducting prospective studies to provide an overview of how snow reliability will evolve in the near future according to different climatic scenarios (e.g. ClimSnow studies by the Abest-INRAE-Météo-France consortium). Figure 9 shows amount of water consumed each year for snowmaking in Avoriaz according to ClimSnow study. The snow reliability simulation tools account for snow management techniques, including grooming and snowmaking. One of the key outputs of the studies carried out is the estimation of water requirements to produce the volumes of snow needed to maintain snow reliability although without accounting for the local water availability. Therefore, it is crucial for ski area operators to have a better understanding of water resources and their availability in the catchment areas where ski runs are located. This is essential for ski area operators to evaluate the feasibility of snowmaking projections and determine the conditions under which they can be achieved. For example, even though the Zugspitze in Germany currently has no snowmaking equipment, between 1961/62 and 2013/14, the Zugspitze experienced a significant decrease [45] in the number of days on which the ski resort could produce snow, with an average decrease of 0.15 days per year in October and November, and 0.14 days per year in December.

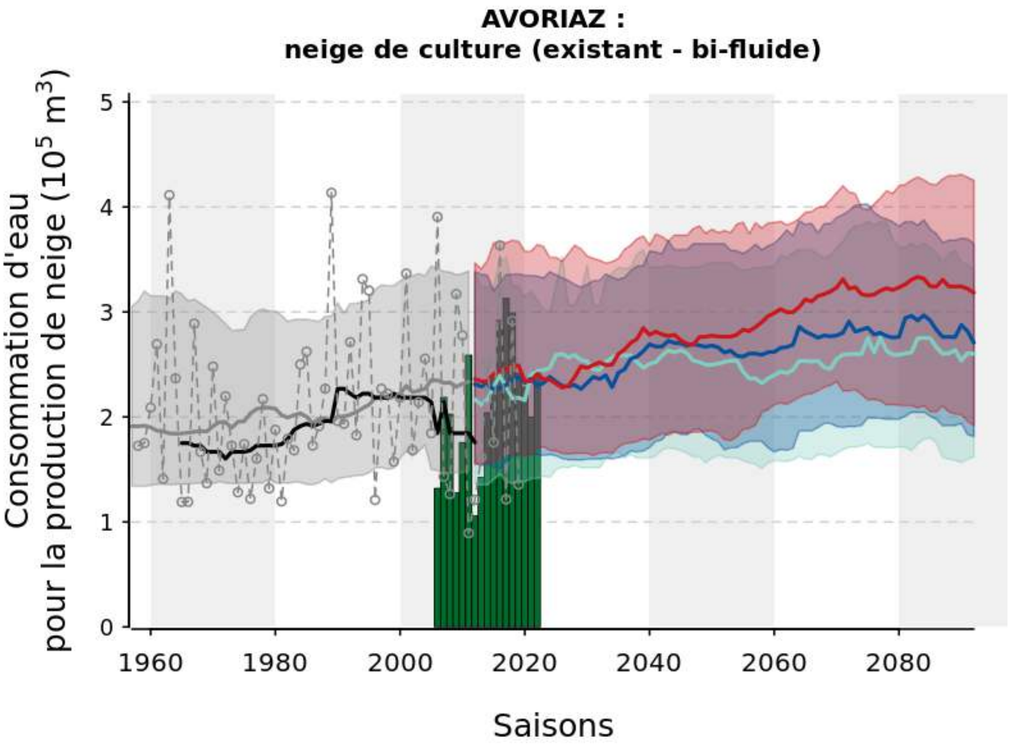

Figure 9: Amount of water consumed each year to produce artificial snow in Avoriaz. The actual values of the last years are represented in green, whereas the curves show the future evolution according to different RCP scenarios (RCP2.6 in light blue, RCP4.5 in dark blue and RCP8.5 in red). An increase in the consumption indicate that artificial snow will have to compensate more and more the lack of natural snow. (Source: ClimSnow study 2024.)

In addition to increasing water requirements, ski resorts are confronted with a discrepancy between the water available and its utilisation for tourist-related activities. Indeed, the volume of water in mountain areas is at its highest in spring, surpassing that of any other season. Water reservoirs play a pivotal role in the strategy to face climate change. The construction of water reservoirs for snowmaking has two essential features. Firstly, it ensures a more even distribution of withdrawals throughout the year. Secondly, it leads to an increase in total withdrawals, in anticipation of deteriorating snow conditions in the future due to climate change. Stakeholders therefore have an expectation of greater knowledge regarding the availability of water resources and any competition for its use with other stakeholders, irrespective of the season.

2.5 Pilot development plan

A series of workshops are scheduled to take place in the coming weeks, inviting a wider group of stakeholders from each pilot site to attend. In each pilot, a Local Working Group (LWG) is being created, gathering members of ski resort's staff (operation manager, snowmaking service, grooming service, etc.) and stakeholders who will be able to provide the information needed to support decision making in the field of drinkable water provision, agricultural or industrial uses.

The precise location of the various water catchment points used for tourism needs in the two pilot resorts will soon be defined by each LWG. It is essential to define these points to start the hydrological modelling process. In addition, information on legal constraints, water uses (drinking water, agriculture, etc.) and management practices, local needs and issues and specific snowmaking planning will be gathered.

In terms of the analysis of water management, workshops on water management will be organised at each site. These workshops will consider the specific role of the stakeholders, the water uses and the current and future needs. Table 3 shows the schedule for the tasks that need to be completed in Pilot 2. Considering the experience gained from previous droughts and the strategies that ski area operators have implemented, a workshop is planned to define a risk matrix for water usage in both pilots. The objective is to collaborate with LWG stakeholders to define the likelihood of episodes of stress on water resources due to drought, and to assess the impact on their respective activities. The objective is to establish which critical risks fall within the remit of integrated water management governance, which medium risks fall within the remit of operational management, and which low-impact but high-probability risks are the responsibility of ski area operators. Figures 10 illustrates the primary tasks to be completed in conjunction with the ski resorts participating in the project. The diagram also shows the interactions associated with the project pilots and the contributions of the Local Working Groups.

Snow and hydrological simulations will be performed in the coming months to estimate the future water availability in each pilot ski area. The hydrological simulations will be performed by CIMA for La Thuile, by Abest-INRAE for Avoriaz, and by TUM for Zugspitze. The snow simulations will be performed by Abest-INRAE using as input meteorological forcings provided by LMU. This will allow to compare water availability and water needs and to estimate the capacity to produce snow in the future.

It is considered imperative that the work and meetings undertaken by Local Working Groups enable the dialog between all their members. For the Zugspitze local working group, and given that Absest and INRAE do not speak German, it has been agreed that Absest and INRAE will produce the documents necessary to carry out the work and facilitate the working group. TUM will facilitate the LWG on site in the local language.

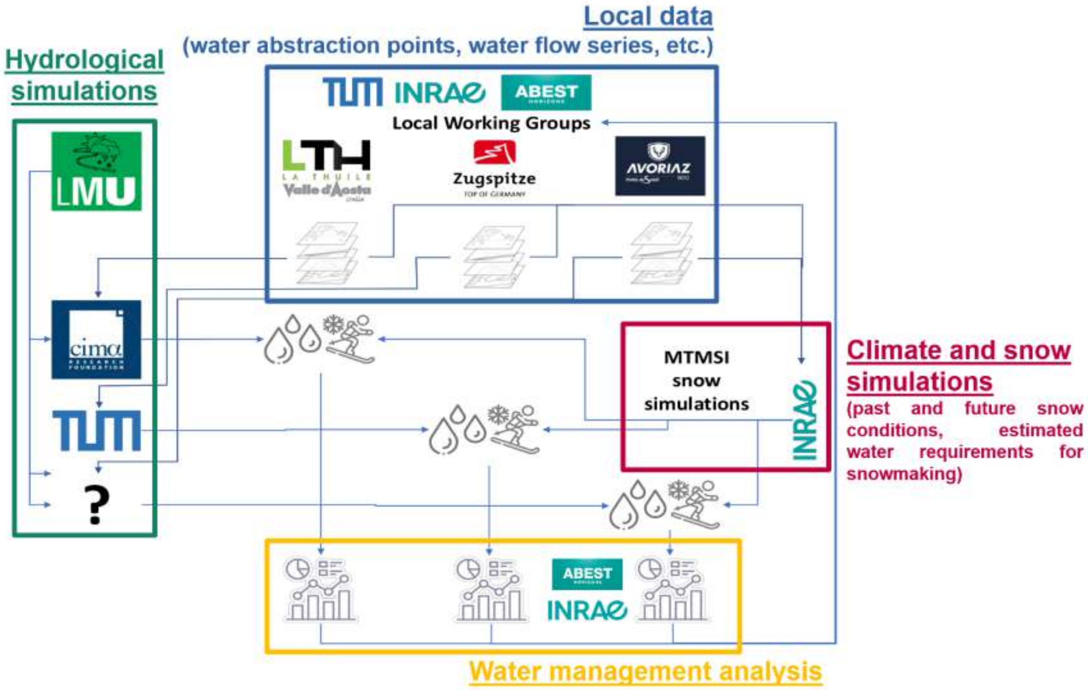

Figure 10: Workflow of the ski resorts's case study. Local data, hydrological and snow simulations will be used to analyze the water management and evaluate the future availability of water to produce snow. (Source: INRAE-Abest)

Table 3: time plan for Pilot 2

Tasks	RP2	RP3	RP4	RP5	RP6
	2025	2025-2026	2026	2026-2027	2027
	mar - aug	sep - feb	mar -aug	sep- feb	mar - aug
Data collection and quality	■	■			
Snow and hydrological simulations		■	■		
Workshops coordination and feedback collection		■	■	■	■
Scenario development			■		
Impact analysis				■	
Tool development and delivery, Stakeholder training					■

2.6 Risks and Challenges

One issue that arises in modelling is the comparability of the results of hydrological and snowpack models when different meteorological inputs are used. For this reason, it has been decided to feed both hydrological and snow simulations with the same dataset provided by LMU. Hydrological simulations will require temperature and precipitation, while snow simulations will also require humidity, wind speed, surface pressure and the phase of the precipitation.

Obtaining detailed knowledge of the state of water resources can still be challenging in some cases. For instance, not all rivers are equipped with flow measurement instruments. Furthermore, while certain uses have been identified, the quantification of these uses is not always clear. Finally, the information available to those involved in tourism is based on theoretical and sometimes outdated standards, which do not always reflect the current and precise state of water resources.

Table 4: Risk for Pilot 2

Risk	Risk Level	Risk Mitigation
Obtaining consistent results from hydrological and snowpack models	Medium	Using the same meteorological forcing (provided by LMU) to drive hydrological and snow simulations
Obtaining detailed and complete data on local water management and uses in ski areas	Medium	Inviting as many local actors as possible to join the LWGs, relying on Abest-INRAE's expertise in running water surveys in ski areas

3 Pilot 3: Generation of a tool to simulate the Upper Isar hydropower complex under drought conditions, using O11 data for model calibration

3.1 Study area

The study area of Pilot 3 is the Upper Isar River basin, covering 2728 km² across southern Germany (65 %) and northern Austria (35 %). As its name suggests, the river basin is located in the most upper part of the Isar basin and stretches from the river´s source in the Alps to its confluence with the Loisach river near Wolfratshausen. The basin is characterized by steep alpine terrain in the south, gradually transitioning into a sub-alpine environment toward the north. Land cover is dominated by forest (65 %) and grassland (17 %), while the remaining area consists of built-up land, water bodies, and bare soil. The catchment is characterized by a pluvio-nival hydrological regime, where streamflow is driven by both snowmelt and precipitation.

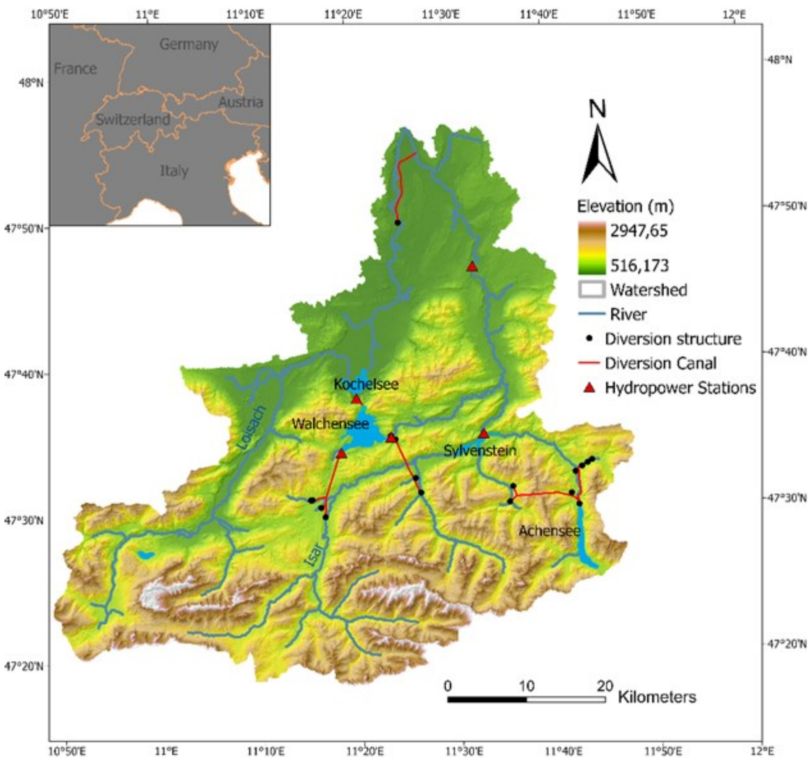

Figure 11: Overview of Pilot 3: The Upper Isar River Basin

The hydrological dynamics of the Upper Isar River basin are further shaped by significant human interventions. In 1924, the Walchensee hydropower station was built. Using the elevation drop of 200 m between the Walchensee and Kochelsee, the power plant reaches a capacity of 124 MW and is one of Germany’s largest high-pressure storage facilities. However, the natural watershed of the Walchensee does not provide sufficient water for power generation. Therefore, in addition to the hydropower plant, a whole system of artificial canals and tunnels was constructed. This system involves damming the Isar River at Krün and diverting most of its flow (on average 13.7 m³/s), along with several smaller tributaries, into the Walchensee. Furthermore, the entire flow of the Rißbach (on average 7.6 m³/s) is redirected into the Walchensee via the Rißbach tunnel. Additionally, since 1927, more diversions have also rerouted water from several Isar tributaries into the Achensee for hydropower generation. Unlike the Walchensee diversions, which eventually return flow to the Isar via the Loisach river, water diverted to the Achensee leaves the catchment entirely, further reducing the Isar's flow by nearly 10 m³/s on average and altering the river's ecology. These flow reductions have resulted in drastically low water levels during dry periods and a decline in water quality. At the same time, a severe flood in May 1940 with a peak discharge of 1440 m³/s in Munich highlighted the need for flood management. In response, the Sylvenstein reservoir was constructed in the 1950s to provide flood protection, low-flow regulation, and additional hydropower generation. [46,47,48]

This highly integrated system of diversions, reservoirs, and regulatory infrastructure has reshaped the basin's hydrology and ecological balance. Because the concession for the Walchensee hydropower plant expires in 2030, this renewal period presents a valuable chance to update and improve water-management strategies. Striking a more effective balance among energy production, ecological preservation, and competing water needs is crucial, particularly given the challenges posed by climate change and the rising frequency of droughts and heat waves.

3.2 Current legislation on water management

The Upper Isar River basin spans both Germany (Bavaria) and Austria. As a result, water management is governed by a combination of national, regional, and European laws. In Austria, the Austrian Water Rights Act of 1959 (WRG) [49] is the central regulation concerning water resource management. The regulation of water and waterways falls under the responsibility of the federal government, while provincial and district-level authorities are primarily responsible for implementing water policy measures. In Germany, the Federal Water Resources Act (WHG) [29] provides the main legal framework for water management, which is further implemented and supplemented by state-level laws such as the Bavarian Water Act (BayWG) [35]. Since 2003, both countries have integrated the EU Water Framework Directive (WFD) into their national and regional legislation. The EU WFD requires coordinated management based on river basins through the development of River Basin Management Plans (RBMPs). The Isar, as part of the Danube basin, is managed through these RBMPs. Closely linked to the RBMPs are the Flood Risk Management Plans (FRMPs), which emerged from the EU Floods Directive. The FRMPs are also managed at a basin level. This ensures cross-border collaboration between Germany and Austria for water protection, flood and drought management, and ecological objectives in line with EU standards. [50,51]

Most of the Upper Isar River watershed falls under Bavarian jurisdiction and follows the regulations stated in the WHG [29] and the BayWG [35]. The key paragraphs of the WHG relevant to Pilot 3 are §33, which defines the need for a minimum river flow, §34, which addresses the continuity of watercourses, and §35, which sets regulations for hydropower usage. For implementing the WHG and BayWG, the Bavarian State Ministry of the Environment and Consumer Protection issued the Administrative Regulations for the Implementation of Water Law (VVWas) [52]. The district administrative authorities and the water management authorities are responsible for the enforcement of these regulations. In the case of the Upper Isar River basin, there are four district authorities who mainly act as the approving authority within their respective areas. Additionally, the water management authority of Weilheim, which also serves as an observer for this Pilot, acts as the official expert and monitors the whole catchment to enforce the regulations.

The water management system in the Upper Isar River basin—including its weirs, diversions, and tunnels—operates according to guidelines established by water-law rulings. However, since these water law rulings were initiated and signed before the EU WFD, many of the current ecological requirements established by the legislation have not yet been implemented. For instance, there is no minimum flow requirement for the Rißbach. Instead, the entire flow (up to a maximum of 12 m^3/s) is diverted to the Walchensee. Requirements for maintaining the continuity of the watercourse are also not met. Even at Krün, no minimum flow was required before 1990. Since then, an environmental flow of 4.8 m^3/s in summer and 3 m^3/s in winter has been established.

The upcoming renewal of the Walchensee hydropower plant concession in 2030, therefore, presents an opportunity to define new water law rulings that enforce the current requirements of water legislation.

3.3 Current practice

Since 2008, the Low Water Information Service [53] has been in operation. It uses 550 gauge stations in Bavaria to monitor discharge and water levels in rivers and lakes, as well as 320 stations for monitoring rainfall. Additionally, it collects data on water temperature and the quality of rivers and lakes. Through continuous measurements, the service stays informed about low flow or low water situations in Bavaria. In such cases, it provides reports on the current situation and its expected development. For forecasting low flow, the service uses LARSIM, the same hydrological model as the flood warning system. By providing online access to measurement data and situation reports, the Low Water Information Service enables decision-makers, particularly those in water management, to respond promptly and effectively during periods of low water levels. The public can also access up-to-date information and forecasts at any time.

In the Upper Isar River basin, the Low Water Information Service is especially important for managing the Sylvenstein Reservoir. The reservoir plays a key role in low-flow regulation, as a minimum flow of 20 m³/s in summer and 10 m³/s in winter must be maintained further downstream. Proper reservoir operation can significantly influence low-flow conditions.

Apart from the Low Water Information Service and the Sylvenstein Reservoir, there are currently no other drought risk management tools in place for the Upper Isar River basin, particularly not for hydropower. Currently, the practice is to divert as much water as legally permitted into the Walchensee, even during drought conditions, and no drought risk management plan is in place. However, with the upcoming renewal of the concession, this is a topic that should be addressed.

3.4 Stakeholders needs

In February 2025, the first stakeholder workshop for Pilot 3 took place at the Technical University of Munich. The goal of this workshop was to get a broad understanding of stakeholders' interests, expectations, and needs. A total of 24 stakeholders from various institutions and authorities took part, including representatives from hydropower operators, nature conservation and environmental organizations, ministries, associations, and scientific institutions. The high number of participants reflects the high level of interest in the project, but particularly in the Upper Isar River basin, which is a hot topic due to the upcoming renewal of the concession for the Walchensee hydropower plant in 2030.

The workshop started with a general introduction about the project and its objectives, followed by a detailed presentation about the development plan for Pilot 3. Afterwards, the stakeholders completed a questionnaire covering four main aspects: 1) Reasons for their interest in the project, 2) Expectations of the results, 3) Possible own contributions to the project, and 4) Open questions and comments.

In general, there is a strong interest among stakeholders in how runoff, water availability, drought, and low-flow periods will change and develop in the future under climate change and how it will impact ecosystems, hydropower production, groundwater recharge, and drinking water supply in the region. The ecological perspective was an important aspect for the stakeholders. In particular, the effects of changing runoff conditions on aquatic and terrestrial habitats, the importance of sustainable bedload management, and the balance between water use and nature conservation were discussed in depth. Stakeholders emphasized that ecological issues must be considered holistically and not just in relation to minimum flows. However, they also mentioned challenges in the compatibility of hydropower and ecological requirements.

The stakeholders expressed specific expectations of the project, including:

- Development of an improved hydrological forecasting model;
- Assessment of future drought and water management scenarios through 2050 and beyond;
- Analysis of water availability and low-flow conditions under future climate, and their effects on hydropower and ecology;

- Holistic view of ecology;
- Practical recommendations for sustainable water use in the Upper Isar, particularly in relation to the upcoming concession renewal;
- Provision of reliable data to support water management and nature conservation planning.

Afterwards, there were interactive group discussions, where mixed groups worked on six predefined questions. Important findings were:

- Improved cooperation between hydropower operators, drinking water suppliers, environmental associations, and authorities could be promoted through enhanced working groups, interdisciplinary dialogues, and a central digital register for water rights decisions;
- Challenges include conflicts of interest between water users, a lack of emergency plans for times of drought, and long-term concessions that restrict flexibility;
- There is a significant gap in comprehensive data on water withdrawals, as well as reliable forecasts for dry periods;
- Hydrological models are essential for water management, but need to become more practical and accurate;
- Scientific findings should be communicated more comprehensibly, e.g., through digital consultation hours and easily accessible information.

In the concluding discussion, it was emphasized once again that minimum ecological requirements should be the basis for all water use. The need for early planning to prepare for periods of drought was also emphasized. Existing working groups, expert opinions, and hydrological models should be used more and developed further.

In summary, the first stakeholder workshop was successful in providing valuable insights into stakeholders' needs and expectations. We are confident that most of these expectations can be addressed within the scope of the project. A central task in Pilot 3, which is outlined in the next section, is the development of drought and water management scenarios and the assessment of their impacts on hydropower, ecology, and other water uses.

One of the key challenges will be addressing ecological aspects in a holistic manner. This would require more complex modelling, such as coupling with sediment transport models, which is beyond the current scope of A-DROP. However, by using the outputs of the developed hydrological model as boundary conditions, we can support ongoing efforts by external working groups that focus on ecological modelling using their own tools.

3.5 Pilot development plan

The main goal of Pilot 3 is to develop a tool or hydrological model that can simulate the entire water management and hydropower system of the Upper Isar River basin over time, with a special focus on drought conditions. The main tasks for Pilot 3 are summarized in the table below.

Table 5: Time plan for Pilot 3

Tasks	RP1	RP2	RP3	RP4	RP5	RP6
	2024-2025	2025	2025-2026	2026	2026-2027	2027
	sep - feb	mar - aug	sep - feb	mar - aug	sep- feb	mar - aug
Data collection and quality						
Hydrological model build up						
Machine learning model build up						
Model calibration, training, and optimization						
Scenario development						
Impact analysis						
Tool development and delivery, Stakeholder training						
Workshops						

During the first reporting period, the focus was on gathering relevant information about the catchment and its water management system, including operational rules. At the kick-off meeting in Bolzano, we initiated discussions with the Water Authority of Weilheim (our observer) and held a follow-up meeting in December in Weilheim to discuss the management system in more detail. In February, we conducted the first stakeholder workshop, where we gathered additional ideas, expectations, and stakeholder needs, as described in the previous section.

3.5.1 Data collection and quality

Gathering the required data for model development and verifying its quality is an essential task. In RP1, we began assessing available datasets for the region. This task will continue until the end of RP3, when integration of data from WP1 is expected. In general, the required datasets fall into three categories: 1. Model setup, 2. Model forcing (inputs) and 3. Calibration and evaluation. For the general model setup, we require a digital elevation model (DEM), a land use map, and a soil map, along with their corresponding databases. The table below provides a summary of the available datasets.

Table 6: Description of DEM, Land use and Soil datasets used for model setup

Variable	Source	Spatial resolution
DEM	Airborne laser scans for Bavaria and Tyrol	5 x 5 m
Land use	CORINE land cover 2018	100 x 100 m
Soil	Harmonized world soil database v1.2	1000 x 1000 m

Meteorological forcing data for the hydrological model can be sourced from the German Weather Service (DWD) [54] and Geosphere Austria [55], both of which maintain extensive measurement networks. The key variable for model calibration is streamflow. Records can be obtained from the Bavarian Hydrological Service (GKD) [56], which provides long-term discharge data at many gauge stations in the Upper Isar basin. Additional discharge data can be obtained from the Austrian Hydrographic Service. The figure below gives an overview of available discharge stations and their record lengths. In addition to publicly available streamflow measurements, discharge data from the hydropower company is also necessary to accurately represent the diversions, reservoirs, and hydropower outflow in the hydrological model.

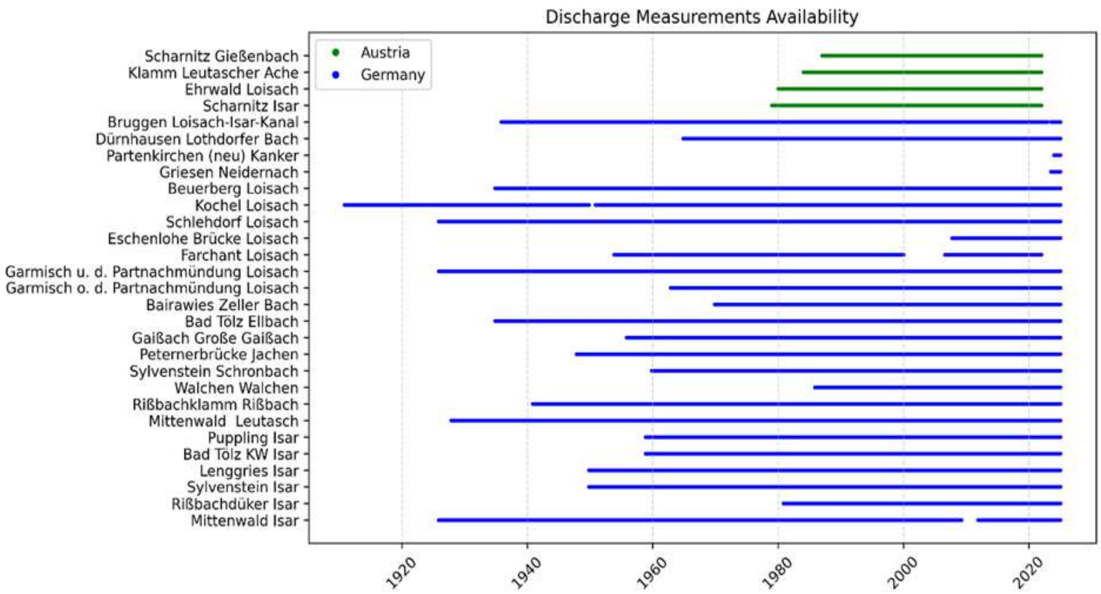

Figure 12: Overview of available discharge stations in the Pilot and their record lengths

Besides streamflow, other variables can be used to evaluate model performance. WP1 datasets, including snow water equivalent (SWE), evapotranspiration (ET), and soil moisture (SM), will be integrated into the modeling chain for either multi-objective calibration or additional evaluation. These datasets will be made available by the end of RP3. Finally, after model calibration and validation, the hydrological model will be forced with projected climate inputs provided by LMU (WP1).

3.5.2 Hydrological model build up

Using the collected data, the hydrological model will be set up. For Pilot 3, we will use SWAT+, a semi-distributed, process-based model designed to simulate both natural and human-influenced processes within a river basin. It is well-suited for representing the water management system of the Upper Isar [57].

3.5.3 Machine learning model build up

To better capture human-influenced flow dynamics and operational rules, we will use data-driven tools. Graph Neural Networks (GNNs) [58], with their flexible graph-based structure, are well-suited for simulating complex managed river networks that include reservoirs, hydropower plants, and artificial channels. A GNN model is under development to represent the Upper Isar's water management system.

3.5.4 Model calibration, training, and optimization

Once the hydrological and machine learning models are established, they will be calibrated and trained using historical data. Although the goal of calibration or training is to achieve a model that is suitable for every situation, the main target is that the models can accurately represent low-flow conditions. Model structures may be further optimized during this process.

3.5.5 Scenario Development

At the beginning of RP4, the second stakeholder workshop will be held. During this workshop, detailed management scenarios will be co-developed with stakeholders.

3.5.6 Impact Analysis

The developed scenarios will be tested under different future climate projections to assess their impact on water availability, hydropower production, and ecological conditions.

3.5.7 Tool development, delivery, and stakeholder training

The calibrated hydrological model will be transformed into a user-friendly tool for stakeholders. The tool will allow users to simulate various drought and management scenarios related to hydropower and water availability. Stakeholders will receive training to use the tool independently.

3.6 Risks and Challenges

Table 7: Possible risks, risk level and their mitigation strategy for Pilot 3

Risk	Risk Level	Risk Mitigation
Operational data of the hydropower plant is not publicly disclosed	High (Confirmed)	We are able to estimate the hydropower plant's outflow from a mass balance of the Kochelsee. [59]
Uncertainty in model output because of model structure, parameter, and scenario uncertainty might complicate decision-making.	Medium	- Ensemble modelling - Sensitivity and uncertainty analysis - Communicate uncertainty clearly to decision-makers

4 Pilot4: Development of a drought-risk assessment dashboard for water governance and hindcast testing of a hydrological forecast model in Valle d'Aosta

4.1 Study area

Aosta Valley (Valle d'Aosta) is an alpine region located in northwestern Italy. It is the smallest and least populated Italian region, covering approximately 3,260 km², and is bordered by France to the west, Switzerland to the north, and the Italian region of Piedmont to the south and east. The region is entirely mountainous, encompassing some of the highest peaks in the Alps, including Mont Blanc (4,810 m), Monte Rosa, the Cervino, and Gran Paradiso. These mountains strongly influence the valley's topography, climate, and hydrology.

The Aosta Valley is characterized by a complex geomorphology, with a main longitudinal valley - traversed by the Dora Baltea River - and numerous steep tributary valleys. The region exhibits a wide range of elevations, which result in sharp climatic gradients, from a temperate alpine climate in the central valley floor to cold, snow-dominated conditions at higher altitudes. Precipitation is highly variable both spatially and seasonally due to strong orographic effects, with average annual totals ranging from less than 600 mm in some inner valleys to over 1,500 mm in exposed mountainous areas. The hydrological network is dense, and snowmelt, glacial contributions, and intense convective rainfall events are all significant drivers of runoff processes in the region.

In recent decades, the Aosta Valley has experienced increasing climatic variability, including the occurrence of prolonged dry spells and seasonal droughts, particularly in spring and summer. These drought periods, sometimes associated with rising temperatures and early snowmelt, have significant implications for water resource availability, agriculture, ecosystem resilience, and the frequency and severity of hydrogeological hazards.

Land use in the region is dominated by natural vegetation, alpine pastures, and forests, with urban settlements and infrastructure primarily located along the valley floor. The combination of complex topography, climate variability, and evolving environmental pressures makes the Aosta Valley a representative and strategically important case study for analyzing hydrological processes and natural hazards in high mountain regions.

4.2 Current legislation on water management

Water management in the Aosta Valley is the result of a multi-level legislative framework that includes European, national, regional, and local laws. This structure reflects the region's complex hydrological system.

At the national level, the first, important legislative act that is relevant to water management in the pilot is the Royal Decree No. 1775 of 1933 [60]. This foundational law, known as the Testo Unico delle Disposizioni di Legge sulle Acque e sugli Impianti Elettrici, introduced the concept of state ownership of surface and groundwater, formalized the concession system for water use, and regulated hydroelectric exploitation. It remains a critical legal reference for water concessions in the region.

Another important source of foundation law is Law No. 36 of 1994 (Galli Law) [61], which redefined water as a public good and introduced the concept of the Servizio Idrico Integrato (Integrated Water Service), aiming for a unified management of water supply, sewage, and wastewater treatment. More recently, legislative Decree No. 152 of 2006 [62] (Environmental Code) transposed EU directives, particularly the Water Framework Directive (2000/60/EC) [26], into Italian legislation. It provides comprehensive guidelines for water protection, quality standards, and basin-level management. Besides that, water related risks, including water scarcity, fall in the risks that the civil protection systems deal with, according to the Decree 2018, Codice della protezione civile [63].

In addition to these long-term pieces of law, a recent, emergency-driven regulation is the Decree-Law No. 39 of 2023 (Drought Decree) [64]: In response to intensifying drought events, this decree introduced urgent measures to improve national water resilience. It provides for the simplification of authorization processes, enhancement of monitoring systems, and the appointment of a special commissioner to coordinate national drought response efforts.

Also note that the region actively participates in River Basin Management Plans under the Po River District Authority, aligning local strategies with European and national objectives. Particular focus is placed on hydropower, ecological flow maintenance, glacier retreat monitoring, and sustainable agriculture.

At regional level, Aosta Valley benefits from an autonomous status (Law No. 4 of 1948) [65], granting it legislative and administrative powers in environmental and water-related domains. An important piece of regional legislation in this context is Regional Law No. 12 of 1997 [66], which governs water resource planning, use, and protection at the regional level. It regulates concessions, prioritizes ecological and drinking water needs, and establishes environmental compatibility requirements for water-related activities. Legislative Decree No. 259 of 2016 [67] then transferred ownership of state-owned public water assets (excluding the Dora Baltea River) from the national government to the Region of Aosta Valley.

Finally, at the municipal level mayors (in their role as local health and civil protection authorities) can issue ordinances to regulate water use, especially during periods of drought or water scarcity. These mayoral decrees often include temporary bans on non-essential water uses—such as lawn irrigation, car washing, or fountain operation—and promote responsible water consumption. In the Aosta Valley's alpine communities, these measures are particularly relevant during summer months when tourism increases water demand and snowmelt-dependent supply becomes less reliable.

4.3 Current practice

In response to the severe water crisis that affected the Aosta Valley in 2022, exacerbated by persistent meteorological anomalies such as above-average temperatures and below-average precipitation, the Regional Government established a technical-political Regional Observatory for Water Crises [68]. This decision was driven by the growing awareness that water scarcity is no longer an exceptional event, but rather a structural issue closely linked to the impacts of climate change in alpine environments.

Formally created through Regional Resolution No. 515/2023 [69], the Observatory is tasked with coordinating monitoring activities, proposing adaptation measures, and evaluating the effectiveness of implemented interventions. It includes the competent regional ministers and representatives from key technical and administrative bodies, such as regional departments, the Functional Centre (https://cf.regione.vda.it/it/), ARPA VdA (https://www.arpa.vda.it/) [64], the BIM (https://www.bimvda.it/), and the CPEL (https://www.celva.it/it/il-consiglio-permanente-degli-enti-locali/). The body operates without additional costs to the regional budget and may also involve, on a voluntary basis, representatives of the sectors most affected by drought conditions.

The Observatory is part of a broader strategy to enhance the resilience of the regional water system, which includes strengthening water intake and distribution infrastructure, building water storage basins, optimizing irrigation practices, and simplifying permitting procedures.

The scientific tools used by the Observatory - developed by the Regional Functional Centre, ARPA Valle d'Aosta, and the CIMA Research Foundation - include a wide range of environmental and hydrological indicators. Among them, water availability is assessed through streamflow data and groundwater levels measured in valley-floor piezometric wells. The ecological status of watercourses is also monitored. Regarding human water use, domestic supply is tracked based on municipal ordinances issued in response to critical conditions, while agricultural use is evaluated through indicators such as meadow and pasture productivity, irrigation demand, and criticalities reported by local irrigation consortia. Hydropower use is analysed based on reductions in electricity production from hydropower plants.

In addition, meteorological data—such as precipitation and temperature—collected by monitoring stations operated by the Functional Centre and ARPA, are used to compute key indices such as the Snow Water Equivalent (SWE) and the Standardized Precipitation Index (SPI), which provide insights into snowpack water content and drought severity, respectively.

4.4 Stakeholders needs

On May 28, 2025, a participatory workshop was held with technical stakeholders from the main institutions involved in water resource management in the Aosta Valley. Participants were organised into deliberately cross-sectoral working groups to encourage exchange across domains and identify common challenges. The session was structured around two main areas: assessment of lessons learned from the 2022–2023 drought events and the co-design of a digital monitoring dashboard.

A first collective exercise focused on the materials used during the 2023 drought response. While the 2022 crisis had already revealed the region's systemic vulnerability to water scarcity, the 2023 experience underscored the difficulties in planning and coordination—particularly in light of strong local variability in water availability. Participants pointed out that information was often scattered and poorly integrated, making it difficult to support informed and timely decision-making, especially at the political level. There was a widespread perception that existing data tools—such as PowerPoint presentations—lacked analytical depth, clarity, and operational utility. In particular, there were difficulties in accessing qualitative data (such as municipal ordinances), which are essential for assessing local administrative responses. The agricultural sector was perceived as being especially fragmented, lacking a shared data system and clear lines of communication.

A key lesson that emerged was the importance of moving from a reactive to a predictive approach. This would require the development of planning and forecasting tools—including the ability to translate technical indicators into accessible formats for non-expert users. Several participants stressed the relevance of certain variables for early warning and strategic response: Snow Water Equivalent (especially in late spring, as a predictor of summer availability), water volumes stored in reservoirs and glaciers, medium-range seasonal forecasts (precipitation and temperature), and real-time meteorological and hydrological indicators (temperature, precipitation, SWE, streamflow, groundwater). Also mentioned were ecological and agricultural variables such as IWR (Irrigation Water Requirements), biomass anomalies, and the timing of livestock transhumance, which could serve as indirect indicators of stress.

Participants highlighted the need to monitor actual water use (particularly for irrigation and domestic supply), to consolidate all hydrological datasets (including pilot studies), and to rationalise data collection processes to make them usable and timely. Automating groundwater monitoring—currently managed manually by ARPA—was also considered a priority. The agriculture sector was again noted as particularly weak in terms of data availability and instrumentation, especially regarding measurements of crop water stress, irrigation volumes, and drought impacts.

The second part of the workshop focused on the design of an integrated digital dashboard. There was general agreement that the platform should be structured by sector—agriculture, hydropower, domestic water use, environment, and health—with each area having its own dedicated space. A shared "home" screen could display the regional synthetic drought severity map, while additional layers would allow users to explore sector-specific indicators in more detail.

Another proposal was to divide the homepage into two main areas: “Monitoring” and “Forecasting”, each with five sectoral sub-sections. This would allow both current conditions and forward-looking trends to be accessed intuitively. For example, the agriculture section could feature dedicated panels for evapotranspiration, productivity, biomass, and IWR, each with corresponding maps, temporal trends, and cross-variable comparisons. A geospatial navigator could allow users to explore the data interactively. There was also a proposal to spatially aggregate information using alert zones, and, where possible or preferable, to base these on hydrological basins rather than administrative boundaries.

Finally, several participants called for the production of an automatically generated summary report every 15 days, with a comment field for the Observatory to provide qualitative context in times of crisis. Some participants expressed interest in developing printable summary materials and intuitive infographics to support rapid communication with municipalities and the general public.

4.5 Pilot development plan

As part of the original development plan, a suite of drought-related indicators is being progressively implemented to support the monitoring functions of the Regional Observatory for Water Crises. These indices are intended to capture different dimensions of drought risk—meteorological, hydrological, agricultural—and will form the analytical foundation for both sectoral dashboards and a synthetic overview product.

Table 8: Timeline of the development plan for Pilot 4

Tasks	**RP1**	**RP2**	**RP3**	**RP4**	**RP5**	**RP6**
	2024-2025	**2025**	**2025-2026**	**2026**	**2026-2027**	**2027**
	sep - feb	**mar - aug**	**sep - feb**	**mar - aug**	**sep- feb**	**mar - aug**
Drought index development						
Severity index development						
Severity index assessment						
Dashboard planning						
Drought bulletin design						
Dashboard development						
Dashboard testing						
Tool delivery						

The following indices are fully developed and available for operational use:

- SPI (Standardised Precipitation Index)
- SPEI (Standardised Precipitation Evapotranspiration Index)
- SWE anomaly (Snow Water Equivalent anomaly)

Work is currently ongoing on the following indicators:

- SMA (Soil Moisture Anomaly)

- LFI (Low Flow Index)
- IWR (Irrigation Water Requirements)

Two additional indices are planned for release in 2026:

- FAPAR anomaly (Fraction of Absorbed Photosynthetically Active Radiation anomaly)
- CDI (Combined Drought Indicator)

As shown in Figure 13, the synthetic severity index will be designed as a regional summary product that combines drought indicators with observed and reported drought impacts, offering an integrated view of severity across sectors. While its development was part of the original system architecture, insights from the stakeholder workshop of May 2025 are helping to refine its spatial structure, aggregation approach, and visual design—particularly in terms of how it captures sector-specific vulnerabilities and local impact dynamics.

The other main goal of this pilot is to support the activities of the technical-political Regional Observatory for Water Crises by developing a combined, data-driven platform to monitor drought risk and identify alert levels at regional and sub-regional level. The core will be an automatic pipeline summarizing drought indices and impact data into the severity index. Integral to this approach will be the development of an online dashboard where such information will be accessible to the public.

This pilot benefits from a long-standing collaboration between the Regional Administration and Fondazione CIMA, which has developed and maintains the regional early warning system for floods and drought. Besides operational snow and hydrologic model, this system includes a variety of drought indices (in particular, precipitation, snow water equivalent, and precipitation vs. Evapotranspiration). Thanks to A-DROP, this system will be enriched with information regarding evapotranspiration.

In parallel, we are performing an in-depth survey of impact data, following several data sources. The first one are historical newspapers, which we are consulting to tease out information on affected municipalities, affected sectors, and timing. In addition, we are performing a survey of existing databases of emergency measures as available in the Regional Administration. The long-term goal is to develop a historical database that will be used to validate drought indices and inform severity levels by establishing procedures to feed this database in real time.

A call for tenders will be launched for the development of the dashboard. Based on the outcomes of the workshop, the specifications will regulate aspects concerning the structure and organization, the contents, the graphic visualization with specific infographics, and the automatic report generation methods.

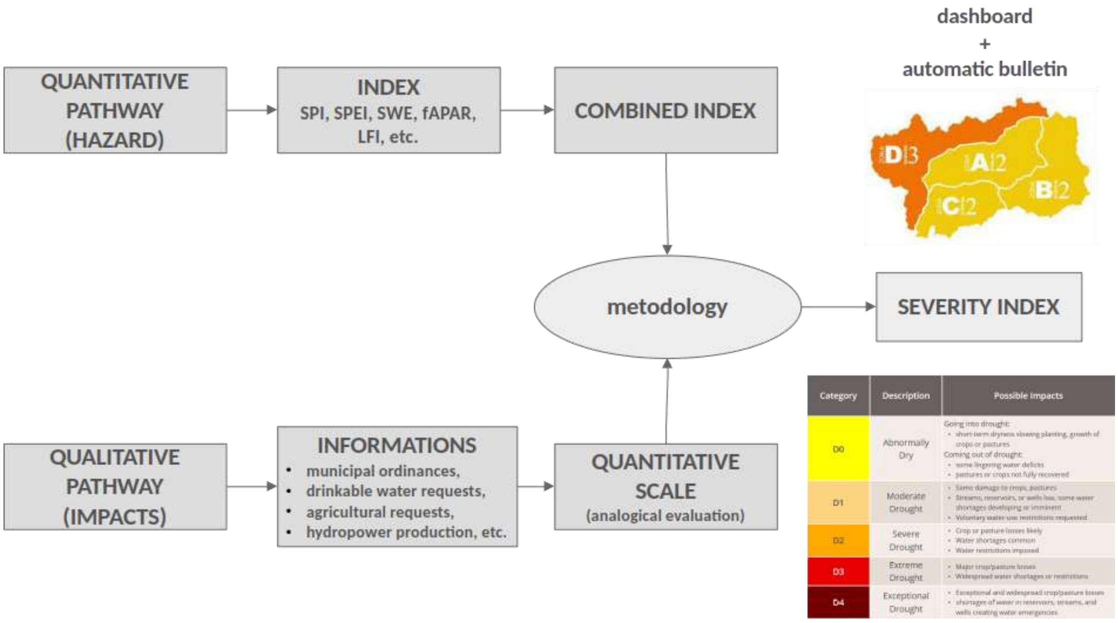

Figure 13: Conceptual framework for the development of an integrated Severity Index, combining two complementary data pathways: on one side, the quantitative component based on traditional drought indices (e.g., SPI, SPEI) and a derived Combined Drought Index; on the other side, a qualitative pathway incorporating near real-time impact data and local observations from the field. The objective is to produce a composite indicator capable of providing a timely and context-aware representation of drought severity. The image presents a preliminary draft of the spatial aggregation approach and the classification into severity classes, which are still under development.

4.6 Risks and Challenges

One challenge is the synthesis of complex and diverse information into meaningful and communicative indexes that effectively reflect the needs of all stakeholders. Designing a platform that is both user-friendly and comprehensive in terms of content represents another major challenge. Given that the final target audience includes policy makers, the tool must be adapted to their specific needs, with a particular focus on accessibility and clarity.

Another critical aspect is the production of reports that are straightforward, easy to interpret, and accessible even to non-technical users. Ensuring that the outputs are concise and visually clear is essential for effective decision-making support.

From a data perspective, it is necessary to assess the availability, consistency, and resolution—both spatial and temporal—of the quantitative data feeding into the platform to develop suitable indexes. Additionally, the collection of qualitative data (such as civil protection interventions and municipal ordinances) presents a further challenge, as these information flows are often not automated and require dedicated efforts for retrieval and integration.

Table 9: Risk and Mitigation table

Factor	Risk	Risk level	Mitigation
Synthesis of complex information	Difficulty in combining diverse and complex information into coherent indexes	Medium	Establish a structured framework for index creation; Define indicators that reflect stakeholder needs looking at different systems
Quantitative data limitations	Challenges in ensuring availability, consistency, and resolution of data (spatial and temporal)	Low	Identify priority data gaps; establish protocols for data harmonization and integration; explore use of proxy or complementary datasets
Qualitative data integration	Civil protection and municipal ordinance data flows are not automated and require manual effort	Medium	Develop partnerships with data providers; create semi-automated or manual reporting systems with standardized input forms
Platform usability and content comprehensiveness	Risk of developing a platform that is not user-friendly or lacks comprehensive content	Low	Co-design with end-users (especially policymakers); perform usability testing early and iteratively
Adaptation to policymaker needs	Platform may not be sufficiently tailored to non-technical, high-level decision-making requirements	Low	Use simple language, clear summaries, and visual elements; engage policymakers during development to ensure alignment with their needs
Report accessibility	Reports may be too technical, long, or difficult to interpret	Low	Produce concise, visually clear summaries; use infographics and executive summaries tailored for non-technical audiences

5 Pilot 5: Set up and hindcast testing of a machine learning (ML) based hydrological forecast model for the Adige catchment

5.1 Study area

The Adige River is the second longest river in Italy, flowing for 409 km from its source, at 1550 m asl in the Alps, to the Adriatic Sea. Its watershed is located in northeast Italy, covering an area of 12.100 km². It crosses six provinces, from the Autonomous Provinces of Bolzano-Bozen (62% of the overall basin) and Trento (29%) to the Provinces of Verona, Padova, Rovigo and Venezia (all of them summing to 9%) (Figure 14). A continental climate characterises the climatic conditions of the entire basin, with cold winters and rainfall maxima during the summer upstream, while hot summers and two precipitation peaks in fall and spring in the plain section of the basin. At higher altitudes, significant water resources accumulate during the winter season in the form of snowfall, which are mobilised during spring. This situation determines the main "nival" hydrological regime of the basin area, characterised by a general high availability of water in the warm season (with and average discharge of about 350 m^3s^{-1}) and low water availability during winter (average discharge of about 150 m^3s^{-1}) [70].

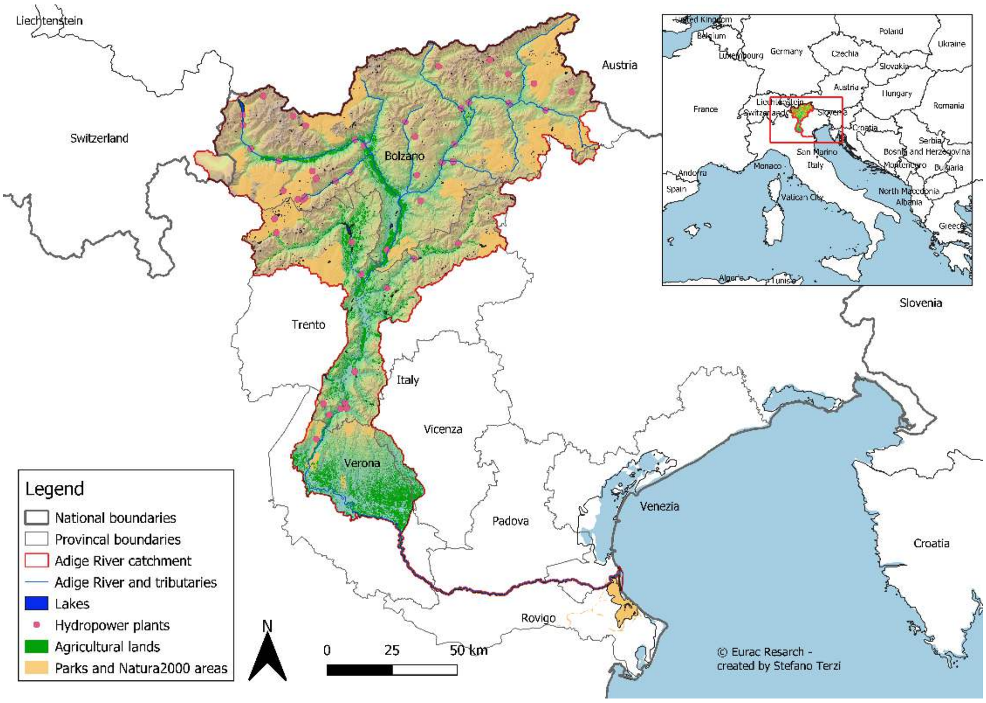

Figure 14: The Adige river basin, the study area of Pilot 5

5.2 Current legislation on water management

Italy is a democratic republic governed by a bicameral parliamentary system and a multi-level administrative structure consisting of regions, provinces, municipalities, and metropolitan cities. The national territory is divided into 20 regions—15 with ordinary status, including Veneto, and 5 with special autonomy due to their unique cultural, linguistic, or geographical characteristics. Among these, Trentino-Alto Adige/Südtirol holds a distinctive position, composed of the autonomous provinces of Trento and Bolzano, which exercise almost the entirety of regional powers through their own legislative, administrative, and financial institutions (Art. 116 and 117 of the Italian Constitution; Special Statute for Trentino-Alto Adige, Constitutional Law No. 1/1948, amended by Constitutional Law No. 3/2001) [71].

In terms of environmental governance, and particularly water resource management, this special autonomy grants Trento and Bolzano substantial legislative competence. They are responsible for drafting and implementing regional/provincial Water Protection Plans (Piani di Tutela delle Acque - PTA), which regulate the use, conservation, and quality of water resources within their territories, in accordance with both national and EU directives.

Water resource management in the Adige River Basin is framed by EU Directive 2000/60/EC (Water Framework Directive - WFD) [26], which requires all EU member states to achieve “good status” for all water bodies. Italy implements the WFD through Legislative Decree No. 152/2006 (Environmental Code) [62], which defines the principles of integrated, basin-based management of water resources across administrative boundaries.

At the basin level, the Adige River Basin is part of the Eastern Alps Hydrographic District (Distretto Idrografico Alpi Orientali), established by Legislative Decree No. 152/2006 [62]. The Authority of the Eastern Alps District (Autorità di Bacino Distrettuale delle Alpi Orientali) is tasked with the preparation of River Basin Management Plans (Piani di Gestione del Distretto Idrografico - PGD) and Flood Risk Management Plans (Piani di Gestione del Rischio Alluvioni - PGRA). These plans provide strategic frameworks for water protection, flood mitigation, and sustainable use across the entire basin [72,73].

Despite the robust legislative framework, coordination between national, regional, and local authorities remains complex, particularly due to overlapping competencies between the Autonomous Provinces of Trento and Bolzano and the Veneto Region. While the Provinces have substantial autonomy, the Eastern Alps Hydrographic District Authority plays a key role in harmonizing planning efforts across regional boundaries, particularly for transboundary issues such as drought risk, water abstraction, and ecological protection.

5.3 Current practice

The water of the Adige River is intensively used for different purposes. Hydropower exploitation represents the dominant water use and the major cause of alteration of the natural hydrological regime in the catchment. Most of the hydropower production is performed by 34 large hydropower plants with a total nominal power of 650 MW [74]. In the lower part of the catchment water is strongly used for irrigation where the two major irrigation channels “Biffis” and “Leb” are taking up to 135 and 35 m^3s^{-1}. Towards the outlet water is used also for freshwater supply and is important to leave at least 80 m^3s^{-1} to prevent marine saltwater intrusion during low flow situations. The complex and diverse water use situation in the Adige basin leads to disputes and tensions for a multi-sector and geographically equitable water management and governance, especially during drought conditions. Although integrated water management systems within the Adige river basin exist (e.g. the Public Water Use General Plan in the Autonomous Province of Bolzano and Trento and the Regional Plan for water protection in the Veneto region), the ongoing combination of the climate change effects on temperature, rain and snowfall; an increasing anthropogenic water demand and; a lack of synergy among the provinces is already now exacerbating water tensions and disputes across sectors and provinces.

Two recent droughts in spring 2017 and in 2022–2023 have brought attention to competing demands for water use. Both of drought events were related to poor snow winters, followed by dry spring and hot summers [75]. Hydropower managers were requested to release water from reservoirs to supply downstream areas, which has led to upstream and downstream challenges, economic and ecologic impacts [76].

The Permanent Observatory on Water Use, coordinated by the Eastern Alps Hydrographic District Authority and with representatives from all relevant water management institutions, oversees and manages water crises in the Adige basin. It plays a crucial role in water governance and has been effective during emergencies but still faces ongoing challenges in regional coordination and data sharing, as highlighted by the EU project Nexogenesis [77]. In practice, various institutions employ different monitoring and modelling tools to assess water availability. It was also observed that adopting a more proactive approach to drought management—by utilizing early indicators such as the snowpack water storage in the mountainous part of the region—could greatly benefit the effective handling of such crises.

5.4 Stakeholder needs

We directly collected user needs during three events, the kick-off meeting, a subsequent workshops (on the 27th of February 2025), and event organized by Eurac as a collaborative effort between multiple projects, the Adige Water Fair (Adige Water Fair - Eurac Research, 19-20th of May 2025) [78]. Additionally, we prepared and sent an online survey to the participants.

We distinguish between two types of stakeholders, i.e., the observers who provide the target needs that we should consider for evaluating the prototype, and the other stakeholders who share an interest for the prototype and bring needs that are not binding. The observers are from regional administrations and agencies operating across the Adige River basin. A list of stakeholders is available in Table 10. Stakeholders can be distinguished by area of interest (e.g. upstream-downstream), role, and sector.

Table 10 – Stakeholder analysis for Pilot 5

Stakeholder	Role	Description	Sector
Agenzia Provinciale per le Risorse Idriche e l'Energia (APRIE)	Observer	The Provincial Agency for Water and Energy Resources implements regional energy regulations, manages authorizations and concessions, oversees the use of public water resources, supports energy planning, coordinates with national water authorities, and promotes research and initiatives for sustainable energy and water use in the Autonomous Province of Trento.	Water & Energy management
Bolzano Civil Protection	Observer	The Civil Protection Agency of the Autonomous Provice of Bolzano, handles forecasting, prevention, crisis management, and reconstruction through specialized expertise, efficient decision-making, and close cooperation with the state, municipalities, and volunteer organizations.	Emergency
Autorità di Bacino Alpi Orientali (AdB-AO)	Observer	The River Basin Authority carries out planning activities for hydrogeological protection, the creation of hazard and risk maps, and the safeguarding of water resources and aquatic environments.	Water management
ANBI Veneto	Stakeholder	ANBI Veneto represents and coordinates agricultural professional organizations, and other regional institutions involved in protecting the environment, landscape, and water resources.	Agriculture
Patscheider	Stakeholder	Patscheider is an engineering company that oversees the development of the new irrigation management plan for the Autonomous Province of Bolzano.	Agriculture
Acquevenete	Stakeholder	Acquevenete is the integrated water service provider for 107 municipalities across the provinces of Padua, Rovigo, Vicenza, Verona, and Venice.	Water supply
Dolomiti Energia	Stakeholder	Dolomiti Energia is the commercial branch of the Dolomiti Energia Group, created to provide energy to households and businesses.	Hydropower

Each stakeholder expressed a need for information relevant for managing drought risk by using a set of attributes from a controlled vocabulary. In the following paragraphs, we report the results from the analysis of their needs which we translated into requirements that should be verifiable. We conclude the section by presenting a summary of the key requirements that should guide the development of the pilot's prototype.

In general terms, there is a consensus among stakeholders that better knowledge and sharing of information on the water available in the system could benefit drought management. There is also a clear awareness that climate change could exacerbate conflicts and increase water scarcity situations, especially during hot summers and during dry winter snow droughts.

The Adige basin lacks a drought seasonal forecasting and early warning system, and stakeholders recognize that such a system could improve their decision-making processes in different ways, for example, supporting the coordination among actors presenting a single shared source of information. It should be noted that at the long-range scale (7 months) a legal framework to norm the stakeholder actions is missing, but it was overall recognised that contextual information can be very important to inform water management decisions in a transparent manner. Nonetheless and regardless of the temporal scale, there is a general lack of thresholds and protocols in the drought normative, in contrast to the flooding normative. The Drought Management Plan (DMP) published by the basin's authority vaguely defines critical conditions during drought events. The DMP indicates that 3-months forecasts should be monitored to inform regional agencies, but it does not prescribe further actions, mainly because uncertainty at 3-months scale is considered too large. It follows that two knowledge gaps can be highlighted, one related to the definition of drought-related thresholds and the other to the reduction of forecast uncertainty. Finally, we identified an information gap for dedicated forecasts at the sub-seasonal scale to address operational needs.

Regarding an overview of the sector's specific needs, stakeholders in water management and civil protection are interested in information about the seasonal evolution of the components of the water balance and the quantification of water availability and deficits which can be useful for prioritising preparatory actions. Stakeholders in the agriculture sector are interested in seasonal forecasts to understand which crop is best to plant given future water conditions, to plan crop rotation, and to identify the source of water deficit (e.g. groundwater, river, reservoirs) that could adversely affect different irrigation districts.

To present the results from the requirements analysis, we list the stakeholders and their hydrological system component (i.e., river, groundwater), geophysical quantity, and indicator of interest in Table 11 –, whereas in Table 3 we show the requirements in terms of temporal (resolution, range, lead time, critical period) and spatial (resolution, extent) characteristics of the information.

Table 11 – Table describing indicators of interest for Pilot 5 stakeholders

ID	Stakeholder	Component	Quantity	Extent or Location	Indicator	Threshold	Description
1	APRIE, ANBI Veneto, AdB-AO	River	Discharge	Trento Ponte San Lorenzo	Days below threshold and relative volume deficit	80 m^3s^{-1}	When the discharge of the river Adige crosses the thresholds the downstream agriculture and water supply are impacted
2	APRIE, Civil Protection, AdB-AO	River	Discharge	All river reaches	Low Flow	90 percentiles	Low flows represent dry periods that can affect water use
3	APRIE, Civil Protection, AdB-AO	River	Discharge	All river reaches	Standardized Flow Index (SFI)	-	The SFI is in the list of official indicators of hydrological drought released by the Instituto Superiore per la Ricerca Ambientale (ISPRA)
4	APRIE, AdB-AO	River	Discharge	All river reaches	Days below threshold and relative volume deficit	Deflusso Minimo Vitale (Ecological Flow)	Ecological functioning of the river ecosystem
5	APRIE, AdB-AO	Land	Evapo-transpiration Precipitation	Adige basin	Standardized Precipitation Evapotranspiration Index (SPEI)	-	Agricultural drought
6	Civil Protection	Cryosphere	SWE	Alto Adige	Standardized Snow Water Equivalent (SSWE)	-	The SSWE is in the list of official indicators of hydrological drought released by the Instituto Superiore per la Ricerca Ambientale (ISPRA)

Table 12 – Properties of the indicators

ID	Indicator	Temporal resolution	Lead time	Critical period	Spatial resolution
1	Days below threshold and relative volume deficit	Week	3 months	March-August	Subbasin
2	Low Flow	Week	3 months	Jan-Dec	Subbasin
3	Standardized Flow Index (SFI)	Month	3 months	Jan-Dec	Subbasin
4	Days below threshold and relative volume deficit	Month	3 months	March-April	Subbasin
5	Standardized Precipitation Evapotranspiration Index (SPEI)	Month	3 months	March-August	500 m
6	Standardized Snow Water Equivalent (SSWE)	Month	3 months	March-April	500 m

An early warning system should be based on indicators, indices, and thresholds. As mentioned above, drought thresholds are scarce to non-existent. The only available thresholds communicated by the stakeholders are relative to river discharge, which is used as an indicator of water scarcity. The stakeholders in agriculture, water management and hydropower identified in the discharge at Trento Ponte San Lorenzo and the downstream Boara Pisani two important indicators of water scarcity. The objective is to keep the discharge at Boara Pisani above 80 m^3s^{-1}, by regulating the supply (release from reservoirs) and demand (decrease irrigation) based on the discharge at Ponte San Lorenzo, to avoid inland saltwater intrusion which can adversely impacts drinking water supply, crops and ecosystems. Figure 15 shows the thresholds at Trento Ponte San Lorenzo and relative actions that should be activated to keep a target 80 m^3s^{-1} at Boara Pisani.

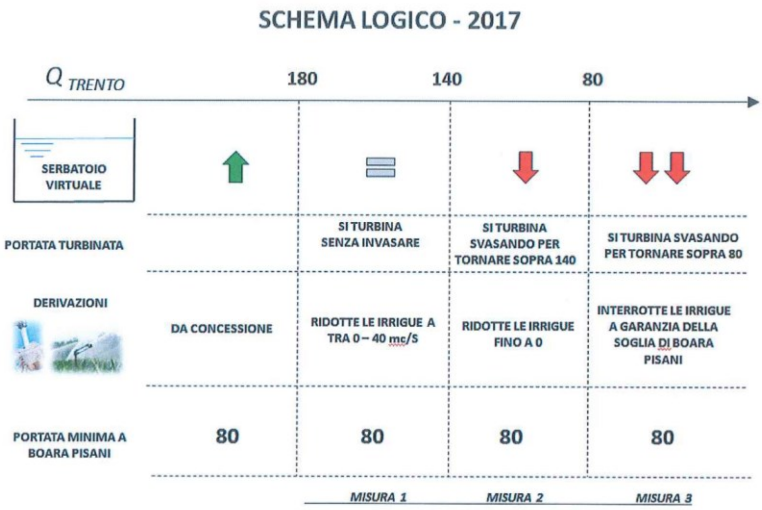

Figure 15 – Action plan of the AdB-AO to tackle the drought in 2017 (Distretto Alpi Orientiali – Misure urgenti per la gestione della carenza idrica, Trento, June 2017)

Another important threshold which represents the ecological interest expressed in the Water Framework Directive is the ecological flow. A study from the province of Trento provides ecological flow thresholds for the main river reaches (Environmental flow map Trentino).

Finally, the analysis of stakeholders' needs identified a set of requirements that should be considered for the development of the pilot's seasonal drought forecast prototype:

- River discharge is required by all stakeholders
- Snow Water Equivalent is a key indicator for future water availability and critical in all sectors
- River discharge measurements should be naturalized to get forecasts of potential water availability
- PET and SSM are necessary for water balance estimation and for computing drought indices (e.g. SPEI)
- Two drought events can be used to test the forecasting system: the spring/summer drought of 2017 and the winter/summer drought of 2022
- The temporal resolution of the output should be at least weekly
- The spatial resolution for land variables should be at least 500 m
- The critical period, related to SWE, is spring. Skilful SWE forecasts for the March-May period could be very useful for all stakeholders.

Even if groundwater and reservoirs volumes are very important for many stakeholders they are not within the scope of the objective of the current pilot.

5.5 Pilot development plan

The goal of the pilot is 1) to develop a hydrological seasonal forecast system prototype, 2) to assess the forecast uncertainty and skills, and 3) to assess the change in performance due to integration of WP1 data into the forecasting system.

The development plan consists of a set of tasks summarised in Table 12. The first task, requirements elicitation, was described in section 5.2.

5.5.1 Data collection and quality assessment

From the perspective of hydrological system modelling, we can distinguish between forcing, prognostic and diagnostic variables. Forcings are the external system drivers (boundary conditions), prognostic variables are states and fluxes that determine the evolution of the system, and diagnostic variables are output variables that can be used to evaluate the model. We denominate ancillary all the other variables that are needed to parametrize the hydrological model. We provide a summary of the input data currently collected for the use case in Table 13 – Input datasets for Pilot 5.

Table 12 – Timeline of the development plan for Pilot 5.

Tasks	RP1	RP2	RP3	RP4	RP5	RP6
	2024-2025	2025	2025-2026	2026	2026-2027	2027
	sep - feb	mar - aug	sep - feb	mar -aug	sep- feb	mar - aug
Requirement elicitation						
Scenario development						
Data collection and quality						
Model development						
Evaluation						
Integration of WP1 data						
Roadmap for upscaling						
Workshops						

Table 13 – Input datasets for Pilot 5

Dataset	Category	Description	Provider/Source
Austrian Reanalysis with Arome (ARA)	Forcing	Meteorological reanalysis at 2.5 km resolution	Geosphere
Downscaled SEAS-6	Forcing	Climate seasonal forecasts from ECMWF's SEAS-6 system, downscaled to 2.5 km	Geosphere
S3M-ALPS	Prognostic	Snow Water Equivalent	CIMA
ET-ALPS	Prognostic	Evapotranspiration	Eurac research
DIREX	Prognostic	Surface Soil Moisture	TU Wien
FAB-DEM	Ancillary	Digital Terrain Model at 30 m resolution	Fathom
Land cover	Ancillary	Land cover product specialized over the EUSALP region, 5 m resolution	Marsoner et al. (2023)[79]
SoilGrids 2020	Ancillary	Dataset providing Soil texture, organic carbon, bulk density at 250 m	ISRIC – World Soil Information Service

Table 14 – Validation and calibration datasets from Pilot 5

Dataset	Type	Description	Provider
Alpine Drought Observatory discharge	River discharge	Dataset containing river discharge from gauges covering the EUSALP region	ADO portal
Large-SaMple Data for Hydrology for Central Europe (LamaH-CE)	River discharge	Dataset providing river discharge and catchment attributes for several subbasins on the Alpine region	Institute for Hydrology and Water Management, University of Natural Resources and Life Sciences, Vienna
Val Mazia	In-situ soil moisture	Dataset for validating model and EO-based soil moisture	Eurac Research

Additional observations are required for model calibration and validation, such as river gauges, in-situ soil moisture (Table 14).

Regarding quality control, the observations used to calibrate and validate the model are quality checked. Also, the integration of WP1 data into the modelling workflow is conditional to their independent quality assessment that will be carried out in collaboration with the WP1 data providers.

Data collection and quality assessment tasks will be carried out until RP4 (see Table 12), when all WP1 data will be evaluated to be compatible for the integration and when after having received all necessary data from stakeholders.

5.5.2 Scenario development

The system will be evaluated on scenarios that are going to be devised with the stakeholders. For example, APRIE, ANBI Veneto, and AdB-AO are interested in forecasting the 2022 drought at Ponte S. Lorenzo.

5.5.3 Model development

Based on the analysis of stakeholder's needs and the requirements for the characteristic of indicators, the hydrological model should output ET, SSM, SWE and Q variables. To ensure the computation of indicators, the spatial resolution of the model output should be 250 meters, and the temporal resolution should be daily.

The core hydrological modelling solution relies on a semi-distributed physical based model, calibrated by a deep learning emulator and satellite data.

The model development task will be concluded in RP4.

5.5.4 Evaluation

The evaluation task will span up to RP5, and it consists in assessing that each task is fit-for-purpose for the next one and for the final objective of the pilot.

5.5.5 Roadmap for upscaling

Once the system is completed and running on the use case's domain, we are going to devise a plan for the upscaling to the entire EUSALP region. The feasibility study will highlight eventual gaps and challenges to achieve the objective. For this reason, the data collection task prioritises data that are available at the scale of the Alpine region scale.

5.6 Risks and Challenges

A key objective of Pilot 5 is to assess the predictability and its drivers and to evaluate when and where it affects the performance of forecasts, preventing the system to be fit-for-purpose for the stakeholders. The complex weather dynamics of the mountain environment pose a significant challenge to the predictability of hydrological variables at the seasonal scale.

Another significant challenge is the integration of WP1 data into the modelling workflow, especially when variables are jointly integrated, or when anthropic processes, which are not addressed in the model structure, significantly influence the variable dynamic (i.e. irrigation on SSM and ET). To achieve the optimal integration, it is advised to have an estimation of the uncertainty of the WP1 data.

Finally, regarding river discharge, the heterogeneity of the mountain environment (geology, topography, soils, land cover, etc.) and the human influence (hydropower, irrigation, water supply) pose a challenge for the accuracy of low flow's accurate modelling.

Table 15 – Risk and Mitigation table

Factor	Risk	Level	Mitigation
Delay in issuing new SEAS6 system	ECMWF should publish SEAS6 in early 2026	Medium	Use the current SEAS5 system
Poor climate predictability	SEAS6 seasonal forecasts, even if downscaled, does not predict well dry-wet climate anomalies	High	Offer only the lead time months up to when the forecasts are skilful
Data quality	WP1 data does not meet quality criteria for integration into the modelling workflow	Medium	Data is not integrated in the hydrological forecasting system
WP1 data uncertainty	Data uncertainty is not provided	Medium	Resort to simpler integration approaches that don't need observation uncertainty
Model performance	The hydrological model does not perform well on low flows	Medium	Modify model structure; Assess if other datasets can improve the accuracy of low flows (i.e. groundwater time series)

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