Demonstration of Sustainable Hydropower Refurbishment

D2.1 Initial studies for retrofitting with pumped storage

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Executive Summary

Context

The Saut-Mortier power plant (EDF) will be retrofitted with variable-speed reversible generating and pumping units equipped with full-size frequency converters and advanced joint controls. The goal is to optimize facility usage, enhance water regulation for multiple users, mitigate environmental impacts and provide peak power and storage capacity. This includes reducing hydropeaking intensity, lowering temperatures, and controlling algae through managed water releases.

Objectives

Numerical models and hydro-thermal indicators will assess river flow, energy flexibility, and water usage across scales. Changes in flow and temperature will be informed by climate trajectories from the French DRIAS web platform. Insights from the Vouglans Saut-Mortier (EDF) demonstration will guide the transfer of this methodology to other sites. Moreover, the project will produce a manual for implementing the new pumping system using hydrological and thermal models

Task progress

We have improved 1D and 3D reservoir models that were applied by the EDF engineering centre for the impact study of the Mortier-Saut project and collected datasets that were used to design retrofitting pumped storage. We tested their functionality and verified the calibration of this first version of digital twin. This phase led us to consolidate the representation of the thermal dynamics involved by converting all the models to a 3D version.

We are now in the process of qualifying the environmental sensitivity (limnological statistical response to weather forcing + upstream flow-temperature couple) of each reservoir in relation to its management mode. To do this, we have developed a semi-automated tool that can be used to run sets of scenarios and link variable reservoirs sets.

Alongside this action, we produce first flow-temperature series scenarios from the reservoir chain and begin the development of the downstream river model.

1 Presentation of the project

1.1 The Ain hydropower chain

The Ain River hydropower reservoir chain in eastern France is a strategically important system for both energy production and water resource management. It comprises six main installations operated by EDF: Vouglans, Saut-Mortier, Coiselet, Moux, Cize-Bolozon, and Allement (Figure 1). These facilities are distributed along approximately 100km of the Ain River, from the large upstream reservoir at Vouglans to the confluence with the Rhône River.

At the heart of the system is the Vouglans dam, commissioned in 1968, which is the third-largest reservoir in France with a total capacity of 600 million cubic meters (420 million usable). It plays a pivotal role in energy storage and peak power generation, with an installed capacity of 285 MW and the ability to respond rapidly to grid demands. Downstream, the Saut-Mortier plant, one of the oldest in the chain (dating back to the early 20th century), is currently undergoing a major retrofit to incorporate variable-speed reversible units and advanced control systems, making it a central site for innovation in pumped storage and ecological flow management.

The Coiselet and Moux installations serve as intermediate regulation points, helping to stabilize flows and support ecological continuity. Cize-Bolozon, with a capacity of 23 MW and a reservoir of 3.3 million cubic meters, is particularly important for downstream temperature control and hydropeaking mitigation. Finally, Allement, located near the river's confluence with the Rhône, acts as the final regulation node, and is critical to ensure that flow and temperature conditions meet environmental and operational standards.

Together, these reservoirs form a highly coordinated system capable of delivering over 400 MW of power within minutes, while also supporting biodiversity, recreational uses, and could represent a potential leverage to climate adaptation.

Figure 1. The Ain River

Figure 2. Characteristics of Ain reservoir chain

1.2 Saut-Mortier hydropower modernization project

1.2.1 Towards sustainable hydroelectricity

The Vouglans–Saut-Mortier project is a flagship initiative by EDF aimed at modernizing and enhancing the flexibility of the Ain River hydropower system in eastern France by optimizing the use of existing infrastructure (Total power capacity: 84 MW, Total expected energy production: 140 GWh). It focuses on transforming the Saut-Mortier hydropower reservoir into a pumped-storage hydropower facility by installing a new variable-speed reversible pump-turbine unit (with a capacity of 60 m3/s and an output of 17 MW), equipped with full-size frequency converters and advanced joint control systems, enabling operational flexibility. This will allow water to be pumped from the Saut Mortier – Coiselet reservoirs back up to the Vouglans reservoir, effectively turning the system into a pumped-storage unit (PS) capable of storing and releasing energy on demand.

The project has three main objectives:

1. **Boost Renewable Energy Production, Storage and enhance Grid Flexibility**
   The new installation will add 16 MW of capacity and enable the storage of up to **200 GWh per year**, equivalent to the annual electricity consumption of approximately **81,000 people**. This will significantly enhance the region's ability to store surplus renewable energy (especially solar and wind) and release it during peak demand periods.
   In addition, the upgraded system will be able to respond to grid demands in under five minutes, providing a fast and reliable source of dispatchable renewable energy.

2. **Improve Multi-Use Water Management**
   The project is designed to maintain water levels that support **tourism (boating, swimming, fishing),** both on Vouglans and downstream river, while also ensuring **environmental flows** that protect aquatic ecosystems of downstream river, including migratory fish species. The improved control of water releases will also help mitigate hydropeaking effects and downstream temperature fluctuations.

3. **Climate and Biodiversity Resilience**
   The project is designed to reduce the ecological impacts of hydropeaking by enabling more flexible and precise water release operations, which helps stabilize river flows and protect aquatic habitats. It also aims to lower downstream water temperatures during summer, reducing thermal stress on aquatic life, particularly cold-water species. This is achieved through improved thermal management of the reservoir chain. Additionally, the project contributes to better control of algal blooms by regulating flow rates and water residence times, thereby enhancing water quality and overall ecosystem health. Moreover, the project will also contribute to **climate adaptation** by integrating hydrological and thermal modelling tools that anticipate future climate scenarios and should highlight more resilient operation management.

With a total investment of €120 million, the project is co-financed by the French government through agencies such as ADEME, the DREAL, and the Water Agency. It is considered a model for sustainable hydropower development and a key component of France's energy transition strategy.

1.2.2 What is thermal management?

In a cascade of hydropower reservoirs, water tends to warm progressively from upstream to downstream, especially during summer months. This warming is driven by several factors: prolonged exposure of reservoirs to solar radiation, low flow velocities that increase residence time, and continuous heat exchange with the atmosphere. As a result, reservoirs often develop thermal stratification, where water layers of different temperatures and densities form vertically. Typically, this includes a warm surface layer (epilimnion), a transition zone (metalimnion), and a colder, denser bottom layer (hypolimnion). The boundary between these layers is known as the thermocline. As the stratification becomes more pronounced during summer, it strengthens the thermal dynamic decoupling of surface and deep-water masses. While surface water reacts to short-term meteorological change, deeper layer remains largely insulated and exhibits much greater thermal stability.

Under these conditions, higher density cold water released from the deep layers of an upstream reservoir can flow downstream and slide beneath the thermocline of the next reservoir in the chain. Hence, this phenomenon is particularly valuable for thermal management.

With climate change, heatwaves are becoming more frequent, intense, and prolonged, especially during summer months when hydropower reservoirs are already vulnerable to warming. These extreme events can significantly elevate surface water temperatures, intensify thermal stratification, and reduce oxygen levels in deeper layers. In cascade systems, this can lead to cumulative thermal stress downstream, affecting aquatic ecosystems, water quality, and even the efficiency of hydropower operations. Moreover, warmer water holds less dissolved oxygen, which can be detrimental to fish and other aquatic life. Effective thermal management—such as strategic release of colder bottom water or mixing interventions—can help mitigate these impacts, making it a critical tool for climate adaptation in hydropower systems.

In this context, the Vouglans reservoir, located at the upstream end of the chain, acts as a cold-water source due to its large storage volume and significant depth (approximately 100 meters), which are much greater than those of the downstream reservoirs. This potential becomes even more relevant with the planned retrofit of the Vouglans–Saut-Mortier system, which will enable up to four times more water to be mobilized from Vouglans than before.

However, pumping and turbining operations can disrupt this thermal structure by inducing vertical mixing, which may weaken or even eliminate stratification (Guénand et al., 2020). This would lead to a homogenization of water temperatures throughout the reservoir and result in warmer downstream releases—contrary to the intended ecological benefits.

The goal, therefore, is to preserve or enhance thermal stratification in downstream reservoirs, using it as a thermal buffer while maintaining energy production. Achieving this requires fine-tuned and coordinated reservoir management, including anticipating meteorological conditions and natural inflows, as an understanding of the thermal resilience of each reservoir to synchronize water releases and avoid abrupt mixing events.

Ultimately, improving our understanding of the hydro-thermal sensitivities and resilience of each component in the reservoir chain will enhance the system's energy-environmental flexibility, allowing for more sustainable and climate-adaptive hydropower operations.

1.3 Methodology

Strategy

During the design phase of the project, a detailed understanding of the thermal sensitivity of the River Ain and its hydroelectric units was sought to qualify the thermal impacts of the construction of a pump-storage unit and identify management guidelines for resilient hydropower production. This is particularly critical in the context of climate change, where rising air temperatures and altered hydrological regimes can exacerbate thermal stress on aquatic ecosystems.

As part of Work Package 2 (WP2), a comprehensive methodology is being developed (Figure 2). A key innovation of this approach lies in its consideration of downstream water temperature impacts, achieved by improving the management of the thermal budget across the entire chain of hydropower reservoirs.

The methodology leverages advanced numerical modelling tools to simulate hydrological and thermal dynamics at multiple spatial and temporal scales. These models incorporate hydro-thermal indicators that quantify key variables such as river discharge, reservoir stratification, thermal inertia, and energy flexibility. Finally, these models' outputs are interconnected with multi-criteria management tools to comply with project objectives.

To ensure robustness and future relevance, the modelling framework integrates climate projections sourced from the French DRIAS platform. These projections provide localized, high-resolution climate scenarios that inform expected changes in temperature, precipitation, and hydrological patterns. This allows the methodology to anticipate and highlight management adaptation to long-term climate trajectories, ensuring that retrofitting decisions remain effective under future conditions.

At its core are hydrological and hydro-thermal models that simulate the behaviour of the river-reservoir system. The hydrological model MORDOR (EDF) provides watershed-scale hydrology, delivering inflow data to the reservoirs. The 1D/3D models of the Ain hydropower chain simulate both hydraulic and thermal dynamics, including the transport of cold water from the deep layers of the Vouglans reservoir. The 1D Allement–Rhône model extends this simulation downstream to the Rhône confluence, capturing thermal evolution along the river continuum.

These models feed into several analytical modules. The T4.3 Fish Habitat Quality module uses hydro-thermal outputs to assess fish habitat suitability and compute biodiversity footprint indicators. The Co-services component integrates additional socio-ecosystem services as management constraints, such as downstream cyanobacteria management, tourism needs, and hydropower production, enabling trade-off analysis between ecological and socio-economic objectives.

The outputs from these modules are synthesized in the Management block, which compiles hydro-environmental sensitivity indicators to identify critical zones or periods for biodiversity and water quality. By simulating different operational scenarios, the models help identify strategies that balance energy production with ecological constraints, such as maintaining suitable temperature ranges for aquatic life downstream (linked to task 4.3).

All of this information converges into a sustainable management tool that supports operational decision-making. This includes a smart release management system, based on a decision-support abacus that links temperature variation (ΔT) to 48-hour release volumes, Rhône River flow, and meteorological conditions.

Further development is planned for this project to achieve a multi-parameter optimisation engine based on a meta-model that will enable the balancing of energy production, ecological integrity and recreational uses, which is outside the scope of the project. This integrated system will support the adaptive and forward-looking management of the hydropower chain by accounting for the impacts of climate change, the need for energy flexibility, and biodiversity conservation goals.

The methodology is being validated through the Vouglans–Saut-Mortier demonstration site, where real-world data and operational feedback are used to calibrate and refine the models. The ultimate goal is to produce a transferable framework and an operational manual that can guide similar retrofitting projects across other hydropower facilities, promoting a new standard for climate-resilient and ecologically responsible pumped storage systems.

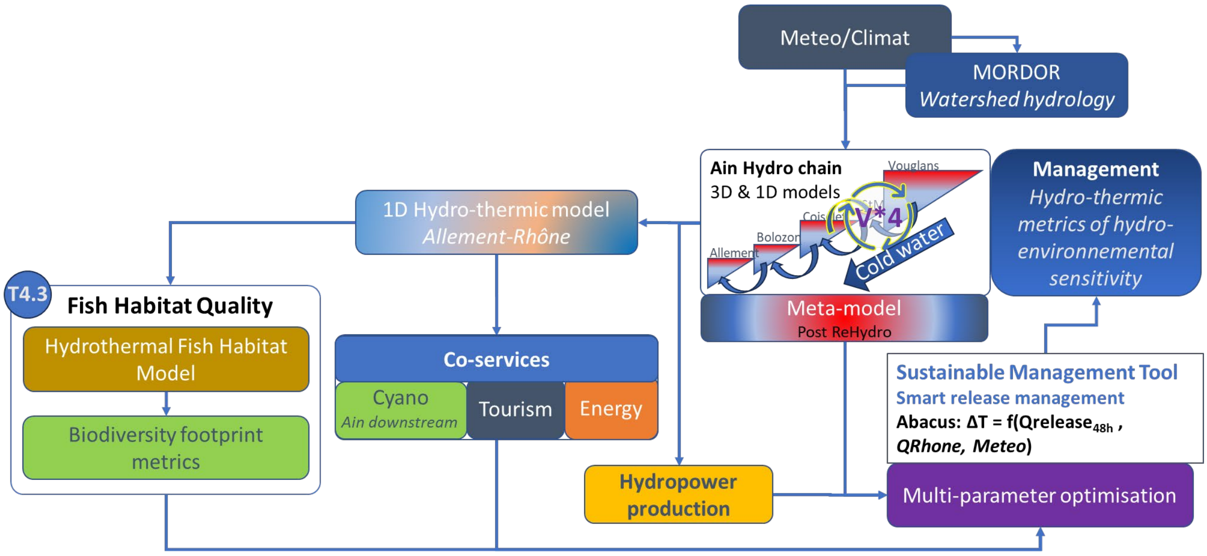

Figure 3. Task 2.2 methodology workflow

1.3.1 Hydrodynamics lake model

1.3.1.1 Choosing hydrodynamic models for hydropower reservoir studies

The selection between one-dimensional (1D) and three-dimensional (3D) hydrodynamic models in hydropower reservoir studies depends largely on the spatial complexity of the system and the level of detail required to represent water withdrawal processes.

1D models, such as the General Lake Model (GLM), DYRESM, or CE-QUAL-W2 (in 1D configuration), are particularly well-suited for deep, narrow reservoirs where vertical stratification dominates and horizontal gradients are minimal. These models simulate vertical temperature profiles and stratification dynamics efficiently, making them ideal for long-term simulations, scenario testing, and evaluating the thermal impacts of selective withdrawal strategies. They typically allow for depth-specific withdrawal configurations, enabling the assessment of how different intake depths affect downstream temperature and reservoir stratification. Its simplicity allows for rapid scenario testing and sensitivity analysis, making it popular in ecological and climate impact studies.

In contrast, 3D models such as ELCOM, Delft3D-FLOW, TELEMAC-3D, or MIKE 3 are necessary when spatial heterogeneity plays a significant role in reservoir behaviour. These models are capable of resolving complex flow patterns, wind-driven circulation, and localized thermal plumes, which are especially relevant near turbine intakes or in reservoirs with multiple inflows and irregular geometry. 3D models provide a more detailed representation of withdrawal effects, including the spatial distribution of temperature and mixing zones, and are essential when assessing localized ecological impacts or designing multi-level intake structures. However, they require significantly more input data, computational resources and expertise in grid generation, turbulence modelling, and calibration of physical parameters. Thus, while 3D models offer greater spatial detail and flexibility, it comes with a steep learning curve and higher data and computational demands.

Ultimately, the choice between 1D and 3D modelling approaches should be guided by the study objectives, the physical characteristics of the reservoir, and the need for spatial resolution in representing withdrawal impacts. While 1D models offer simplicity and speed for system-wide thermal assessments, 3D models are indispensable for capturing fine-scale processes and informing detailed operational strategies in complex hydropower systems.

In our case, preliminary simulations revealed a high degree of thermal resilience in the downstream temperature of the Vouglans reservoir. This finding allowed us to exclude Vouglans from the detailed modelling chain, as its influence on downstream thermal dynamics appeared limited under the tested scenarios. However, due to the hydrological complexity introduced by the pumped-storage operations and the confluence with the Bienne tributary in the Saut-Mortier–Coiselet system, we implemented a 3D hydrodynamic model to accurately capture spatial heterogeneity and localized mixing processes. For the downstream reservoirs at Cize-Bolozon and Allement, where the geometry is simpler and stratification is the dominant process (VIDAL-HURTADO, 2017), we initially opted for a 1D modelling approach. This should provide sufficient resolution for the thermal dynamics while maintaining computational efficiency. However, during implementation, we observed that the model was inaccurate in terms of stratification dynamics.

Nevertheless, here we present some key points on this 1D/3D case-specific dilemma and how to process the implementation of such models. Please refer to the corresponding documentation for further details.

1.3.1.2 1D hydrodynamic lake model

Given the morphological and hydraulic similarities between the Cize-Bolozon and Allement reservoirs, and with the objective of assessing the thermal sensitivity of these systems under various theoretical scenarios, water temperature downstream of both dams was simulated using two similar 1D models. Each model was configured to account for the specific characteristics of the corresponding reservoir, particularly the elevation of water intakes.

Presentation of the software

The one-dimensional hydrodynamic model used in this study is the General Lake Model (Hipsey et al., 2019), developed by the University of Western Australia as part of the Global Lake Ecological Observatory Network (GLEON) initiative. GLM has since been adopted by over 80 research teams and is currently applied to more than 100 lakes worldwide, making it a widely recognized tool in the field of lake and reservoir modelling.

GLM is particularly well-suited for simulating vertical thermal structure in stratified water bodies. It operates with flexible vertical resolution, allowing for detailed representation of temperature, salinity, and density profiles over time. The model accounts for surface heat and momentum exchanges, as well as inflows and outflows such as river inputs, dam releases, and turbine operations. This makes it especially relevant for hydropower applications where thermal stratification and water withdrawal strategies play a critical role in downstream temperature dynamics (Figure 3).

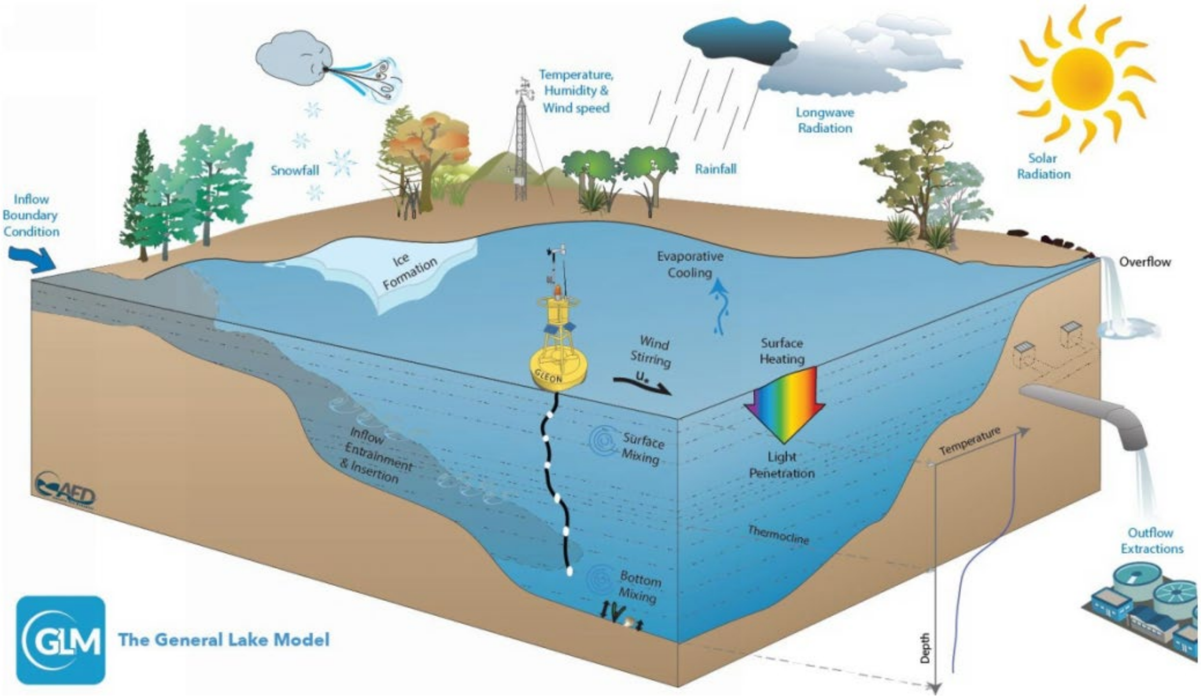

Figure 4.: Representation of simulated processes with GLM

Vertical architecture of the model

GLM (General Lake Model) employs a Lagrangian layer structure with variable vertical resolution (see Figure 4). This approach is based on the DYRESM model (Imerito, 2007) and begins with a user-defined number of layers of equal thickness. As the simulation progresses, the model dynamically adjusts both the thickness and number of layers to optimize resolution in regions where thermal or hydrodynamic gradients are most significant. This adaptive layering ensures that each layer maintains homogeneous physical properties, a key assumption of the model. In well-mixed zones, where temperature and density are relatively uniform, the model consolidates layers into thicker segments. Conversely, in stratified zones - particularly near the thermocline, where temperature gradients are steep - GLM refines the vertical resolution by creating thinner layers.

This allows for a more accurate representation of thermal stratification dynamics, which is critical for simulating reservoir behaviour under varying meteorological and operational conditions.

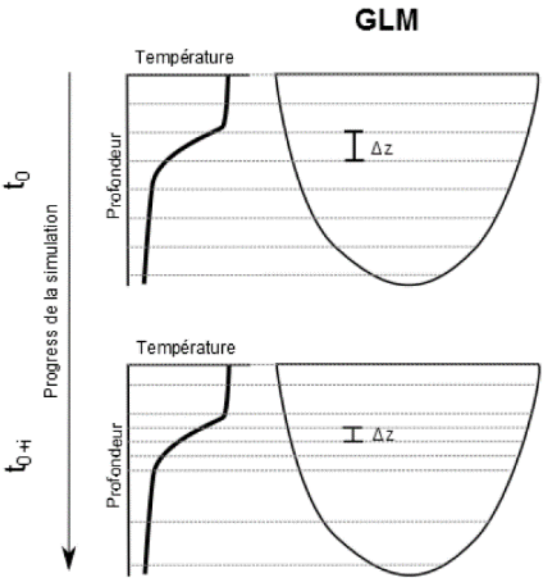

Figure 5. Evolution of the vertical structure of a GLM model

Criteria for applying a 1D model

These models assume horizontal homogeneity, a condition verified through the evaluation of five key dimensionless numbers that characterize the dominant physical processes:

- **Rossby number (R > 1):** Indicates that Coriolis forces have a negligible effect on thermocline deformation, validating the 1D assumption.
- **Froude number of inflows (F_i < 1):** Ensures that pressure forces adjust horizontal density gradients faster than inflows can generate them, maintaining vertical stratification.
- **Froude number of outflows (F_0 < 1):** Similarly, confirms that outflows do not induce significant horizontal gradients, preserving the 1D structure.
- **Wedderburn number (W > 3):** Reflects the stability of the surface layer under wind stress. For W > 3, the thermocline remains stable and horizontal mixing is limited, supporting the 1D approach.
- **Lake number (LN > 1):** Describes the response of the hypolimnion to wind forcing. Values above 1 indicate that internal waves and upwelling are minimal, and the vertical structure remains intact.

A comprehensive thermal study of the Allement reservoir was previously conducted using the EOLE model, a hydrodynamic simulation tool developed by EDF R&D (Vidal-Hurtado, 2017). The results from this study were subsequently compared with simulations performed using the GLM, and the calibration outcomes were found to be highly satisfactory.

During that earlier study, the calculation of key dimensionless numbers for the Allement reservoir over the period 2006–2008 provided valuable insights into the applicability of a 1D modelling approach. First, the Rossby number remained consistently above 1, indicating that rotational (Coriolis) effects were negligible. This is expected given the narrow geometry of the reservoir, where pressure forces dominate over rotational influences, confirming the suitability of a vertically structured model.

The Froude numbers for inflows and outflows showed significant variability. They were generally below 1 during summer, when inflows are low and the reservoir is thermally stratified—conditions favourable to maintaining a 1D structure. However, during episodic high-flow events, the Froude numbers exceeded 1, coinciding with intense vertical mixing and short residence times (less than one day). Under such conditions, stratification cannot be sustained, and water temperature is primarily governed by inflow characteristics. Nevertheless, the short duration of these events limits the deviation from model predictions.

The Wedderburn number (W) and Lake number (LN) also varied seasonally. During periods of strong stratification and low wind speeds (< 5 m/s), W > 3 and LN > 1, indicating stable vertical layering and minimal horizontal mixing—conditions under which the 1D structure is preserved. Conversely, during strong wind events (≫ 5 m/s), both W and LN dropped below critical thresholds, suggesting the onset of upwelling and internal wave activity that disrupts vertical stratification. Although such wind events were relatively infrequent in 2006 (the reference year for the current study), they may still influence short-term thermal dynamics.

In summary, during summer—the most thermally sensitive period—the 1D structure of the Allement reservoir is generally maintained under low wind and flow conditions, which prevail for much of the season. While strong wind events may temporarily compromise the vertical structure, their limited frequency and duration reduce their overall impact. High-flow events, though more common, result in rapid mixing followed by re-stratification, allowing the reservoir to quickly return to a 1D configuration. These findings confirm that the 1D modelling approach remains valid for Allement under most operational and climatic scenarios.

GLM model parameters used

The GLM models used to model the Allement and Cize-Bolozon reservoirs have a common architecture which is detailed below. The model parameters are identical to those already tested and validated by EDF on the Allement reservoir (VIDAL-HURTADO, 2017). The only difference between the models for the two reservoirs is the height of the water intakes.

General model configuration

The model parameters are set using the “glm.nml” file. It contains all the model information, from the capacity curve (Depth-Volume or Depth-Surface) to the Secchi disc, all the flow and meteorological data and the morphological characteristics of the reservoir.

```
! general model setup
!-------------------------------------------------------------------------------
!
! sim_name         [string]  title of simulation
! max_layers       [integer] maximum number of layers
! min_layer_vol    [real]    minimum layer volume (m3 * 1000)
! min_layer_thick  [real]    minimum layer thickness (m)
! max_layer_thick  [real]    maximum layer thickness (m)
! Kw               [real]    background light attenuation (m**-1)
! coef_mix_conv    [real]    mixing efficiency - convective overturn
! coef_wind_stir   [real]    mixing efficiency - wind stirring
! coef_mix_turb    [real]    mixing efficiency - unsteady turbulence effects
! coef_mix_shear   [real]    mixing efficiency - shear production
! coef_mix_KH      [real]    mixing efficiency - hypolimnetic Kelvin-Helmholtz turbulent billows
! coef_mix_hyp     [real]    mixing efficiency - hypolimnetic turbulence
! deep_mixing      [bool]    flag to disable deep-mixing
!
!-------------------------------------------------------------------------------
&glm_setup
   sim_name = 'GLM Simulation'
   max_layers = 140
   min_layer_vol = 0.025
   min_layer_thick = 0.15
   !min_layer_thick = 0.350
   max_layer_thick = 0.6
   !max_layer_thick = 0.900
/
&light
   !-- Light Parameters
   Kw = 0.3
/
&mixing
!-- Mixing Parameters
   coef_mix_conv = 0.125
   coef_wind_stir = 0.23
   coef_mix_shear = 0.20
   coef_mix_turb = 0.51
   coef_mix_KH = 0.30
   coef_mix_hyp = 0.4
!  non_avg = .true.
   deep_mixing = .true.
/
```

Figure 6. Configuration of the 1D model used

Maximum Number of Layers (max_layers)

This parameter defines the upper limit of vertical layers used in the model. The model employs time-varying Lagrangian layers whose thickness adapts dynamically based on the degree of stratification. The user must specify a maximum number of layers, which should remain below the ratio of the reservoir's maximum depth to the minimum allowable layer thickness.

Choosing a lower number of layers can reduce computational time, but if the number is too small, the simulation may fail to converge. To ensure stability and accuracy, the user must also define either:

- min_layer_vol: the minimum volume per layer, and/or
- min_layer_thick: the minimum layer thickness (recommended).

For stratified systems, a minimum thickness between 0.15 m and 0.5 m is suggested. Stronger stratification requires finer vertical resolution.

Maximum Layer Thickness (max_layer_thick)

The maximum allowable thickness for any layer should typically range between 0.5 m and 1 m, depending on the system's depth and stratification intensity.

Light Attenuation Kw

Represents the average light attenuation coefficient over the simulation period. It can be estimated from Secchi disk depth (D_{Secchi}) using the formula:

$$Kw=1.7D_{Secchi}$$

Mixing Efficiency Coefficients

- coef_mix_conv: Convective mixing efficiency. Higher values enhance surface mixing during cooling events (e.g., nighttime or winter conditions).
- coef_wind_stir: Wind-induced mixing efficiency. Based on empirical studies (Spigel et al., 1986; Wu, 1973), a reference value of 0.23 is commonly used. Increasing this coefficient deepens the surface mixed layer in response to wind forcing.
- coef_mix_shear: Shear-induced mixing efficiency. Sherman et al. (1978) suggest values between 0.2 and 0.5, with 0.3 providing good calibration. Higher values destabilize the thermocline and enhance surface-layer mixing.
- coef_mix_turb: Turbulent mixing efficiency. The default value used in GLM is 0.51.
- coef_mix_KH: Mixing efficiency due to Kelvin-Helmholtz instability. Laboratory experiments indicate that 70–90% of shear energy is lost to viscosity (Sherman et al., 1978). Recommended values range from 0.1 to 0.3, with 0.3 as the default.
- coef_mix_hyp: Hypolimnetic (deep water) mixing efficiency. A typical value is 0.5, as proposed by Weinstock (1978).

To activate the deep mixing module, set: deep_mixing = .true.

<u>Lake characteristics and capacity curve</u>

This second section describes the morphology of the lake. Latitude and longitude are used to calculate albedo, while length and width are used for several calculations, such as horizontal transport, length of talweg, etc. The user can choose to give the capacity curve: Rating (H) / Area (A) or Rating / Volume (V). The number of points given by the user in the capacity curve must be defined in *bsn_vals*.

```
!--------------------------------------------------------------------------------
! lake details
!--------------------------------------------------------------------------------
!
! name              [string]
!                     name of the lake
! latitude          [float, minimum = -90, maximum = 90, unit = deg North]
!                     latitude
! longitude         [float, minimum = -360, maximum = 360, unit = deg East]
!                     longitude
! base_elev         [float]
!                     base elevation (m)
! crest_elev        [float]
!                     crest elevation (m)
! bsn_len           [float]
!                     basin length at crest (m)
! bsn_wid           [float]
!                     basin width at crest (m)
! bsn_vals          [integer]
!                     number of depth points on height-area relationship
! H                 [float]
!                     elevations (m)   (comma separated list, len=bsn_vals)
! A                 [float]
!                     area (m2) (comma separated list, len=bsn_vals)
!
!--------------------------------------------------------------------------------
&morphometry
   lake_name  = 'Elipse'
   latitude   = 46.10
   longitude  = 5.42
   bsn_len    = 900
   bsn_wid    = 600
   bsn_vals   = 40
   !   H(m)  A(m2 * 1000) V(m3 * 1000)
   H =  247.5, 248, 248.5, 249, 249.5, 250, 250.5, 251,
                251.5, 252, 252.5, 253, 253.5, 254, 254.5, 255,
                255.5, 256, 256.5, 257, 257.5, 258, 258.5, 259,
                259.5, 260, 260.5, 261, 261.5, 262, 262.5, 263,
                263.5, 264, 264.5, 265, 265.5, 266, 266.5, 267,
                267.5
   A =  0, 5000, 6100, 8500, 12300, 18600, 25400, 37900,
                55000, 79900, 124200, 196800, 268500, 339900, 405300, 478800,
                563600, 637900, 702000, 761700, 820000, 875700, 933700, 998700,
                1073700, 1135000, 1188600, 1251600, 1318000, 1387000, 1467500, 1543500,
                1605600, 1657800, 1699600, 1782400, 1865300, 1948200, 2031000, 2113900,
                2196800
/
```

Figure 7. Capacity curve for the 1D model

Initialisation and simulation duration

The simulation initialization and duration can be defined by the user using several methods. Either from the number of time steps to be simulated, or from the initial and final dates. The time step in seconds must also be defined by the user (i.e.: dt = 3600 = 1h).

```
!-------------------------------------------------------------------------------
! duration of run
!-------------------------------------------------------------------------------
!
! timefmt [integer]
!           method to specify start and duration of model run
!           1: duration computed from number of time steps, MaxN (bogus start
!             date used) [no longer implemented!!]
!           2: duration computed from given start and stop dates (number of time
!             steps MaxN computed)
!           3: duration computed from number of time steps, MaxN (start date as
!             specified, stop date computed)
! start   [string, format = "yyyy-mm-dd hh:mm:ss"]
!           nominal start date
!           This variable is used only if timefmt != 1
! stop    [string, format = "yyyy-mm-dd hh:mm:ss"]
!           nominal stop date
!           This variable is used only if timefmt = 2
! dt        [float, minimum = 0.001, maximum = 86400, unit = s]
!               Time step for integration
! numb_days [number of days to run the simulation ]
!           This variable is used only if timefmt != 2
!
!-------------------------------------------------------------------------------
&time
   timefmt = 2
   start = '2006-01-01 00:00:00'
   stop = '2006-12-31 00:00:00'
   dt = 3600
   num_days=3288
   timezone = 7.0
/
```

Figure 8. Setting the duration and dates of simulations

Output files

The name and output folder of the results is defined by the user. The daily summary of variables is saved in "lake.csv". Potential water outflows from the model, with the variables selected by the user, are saved in the file "overflow.csv".

```
!-------------------------------------------------------------------------------
! format for output and filename(s)
!-------------------------------------------------------------------------------
!
! out_dir           [string]
!                     path to output directory (set permissions)
! out_fn            [string]
!                     name of output netcdf file
! nsave             [integer, minimum = 1, maximum = 86400]
!                     save results every 'nsave' timesteps
! csv_lake_fname    [string]
!                     name of lake.csv lake simulation daily summary information
! csv_point_nlevs   [integer]
!                     number of depths at which to dump a csv time-series file
! csv_point_at      [real]
!                     height from bottom for point csv file(s) (comma separated list)
! csv_point_fname   [string]
!                     name of csv output file(s) (comma separated list)
! csv_point_nvars   [integer]
!                     number of variables to output into csv
! csv_point_vars    [string]
!                     list of names of variables to output, - order IS important
! csv_outlet_allinone [bool]
!                     put all outflow data into the same csv file
! csv_outlet_fname  [string]
!                     name of csv output file(s) (comma separated list)
! csv_outlet_nvars  [integer]
!                     number of variables to output into outlet csv
! csv_outlet_vars   [string]
!                     list of names of variables to output
! csv_ovrflw_fname  [string]
!                     name of csv file to record amount and quality of overflow
!
!-------------------------------------------------------------------------------
&output
   out_dir = '.'
   out_fn = 'output'
   nsave = 2

   csv_point_nlevs = 1
   csv_point_fname = 'WQ_'
   csv_point_at = 0.
   csv_point_nvars = 1
   csv_point_vars = 'temp'

   csv_lake_fname = 'lake'

   csv_outlet_allinone = .false.
   csv_outlet_fname = 'outlet_'
   csv_outlet_nvars = 3
   csv_outlet_vars = 'flow',
                     'temp',
                     'salt',
   csv_ovrflw_fname = "overflow"
/
```

Figure 9. Setting output files

Thermal profiles and initial conditions

The maximum initial depth must be defined by the user (initial depth - maximum depth) as well as initial temperature and salinity profiles or the number of points on the vertical (num_depths). The model uses linear interpolation between the points given by the user. The temperature values are updated according to the simulated scenarios.

```
!------------------------------------------------------------------------------
! initial condition profiles
!------------------------------------------------------------------------------
!
!   lake_depth     [float]   initial lake depth (m)
!   num_depths     [integer] number of depths provided for initial profiles
!   the_depths     [float]   the depths of the initial profile points (m)
!   the_temps      [float]   the temperature of the initial profile points (C)
!   the_sals       [float]   the salinity of the initial profile points (psu)
!
!------------------------------------------------------------------------------
&init_profiles
    lake_depth = 19.5
    num_depths = 3
    the_depths = 0.49,4.26,19.00
    ! GLM
    the_temps  = 4.00,4.00,4.00
    the_sals   = 0,0,0
```

Figure 10. Initials conditions

Weather conditions

Meteorological Forcing Configuration in the Thermal Model

To incorporate meteorological forcing, the weather module must be activated by setting: meteo_sw = .true.

Once enabled, the user must configure the following parameters:

Radiation and Cloud Cover Settings

- **lw_type**: Specifies the type of input data used to compute longwave radiation:
  - LW_IN: Use if incident longwave radiation data is available.
  - LW_NET: Use if net longwave radiation data is available.
  - LW_CC: Default option when longwave radiation is estimated from cloud cover data (recommended due to limited availability of direct measurements).
- **rad_mode**: Selects the radiation computation method based on available input data. For simulations using hourly or tri-hourly solar radiation and cloud cover data, **option 1** is typically recommended.
- **albedo_mode**: Determines how surface albedo is calculated. Several methods are available as described in the GLM manual (Hipsey et al., 2019).
- **cloud_mode**: Defines the method for estimating cloud cover. Four methods are available. Methods 1 and 2 have shown the best performance for reservoirs studied in this project.

Surface Exchange Coefficients

- **cd**: Wind drag coefficient (momentum transfer). Higher values increase wind shear stress and enhance vertical mixing. Typical range: 0.001 – 0.003 with a reference value: **0.0013** (Salençon and Thébault, 1997)
- **ce**: Latent heat exchange coefficient. Increasing this value enhances latent heat flux and surface cooling, indirectly promoting convective mixing and deepening the surface mixed layer. Typical range: 0.001 – 0.003 with a reference value: 0.0013 (Wahl and Peeters, 2014)
- **ch**: Sensible heat exchange coefficient. A higher value increases the sensible heat flux, which can either warm or cool the surface depending on the air–water temperature gradient. Typical range: 0.001 – 0.003 with a reference value: 0.0013 (Wahl and Peeters, 2014)

Meteorological Data Input

The user must provide the name of the meteorological data file (e.g., Meteo.csv). The data frequency must be specified, especially if it is sub-daily (e.g., hourly or tri-hourly).

```
!-------------------------------------------------------------------------------
!
!   met_sw         [bool]   switch to include surface meteorological forcing
!   lw_type        [string] type of longwave data supplied (LW_IN/LW_CC/LW_NET)
!   rain_sw        [bool]   include rainfall nutrient composition
!   snow_sw        [bool]   include snowfall (m/d)
!   atm_stab       [bool]   account for non-neutral atmospheric stability
!   catchrain      [bool]   flag that enables runoff from exposed banks of lake area
!   rad_mode       [integer] short and long wave radation model configuration (see manual)
!   albedo_mode    [integer] shortwave albedo calculation method
!   cloud_mode     [integer] atmospheric emmisivity calculation method
!
!   meteo_fl       [string] name of file with meteorology input data
!   wind_factor    [float]  wind multiplication factor (-)
!   wind_factor    [float]  wind multiplication factor (-)
!   rain_factor    [float]  wind multiplication factor (-)
!   sw_factor      [float]  wind multiplication factor (-)
!   lw_factor      [float]  wind multiplication factor (-)
!   at_factor      [float]  wind multiplication factor (-)
!   rh_factor      [float]  wind multiplication factor (-)
!
!   ce             [float]  bulk aerodynamic coefficient for latent heat transfer
!   ch             [float]  bulk aerodynamic coefficient for sensible heat transfer
!   cd             [float]  bulk aerodynamic coefficient for transfer of momentum
!   rain_threshold [float]  rainfall amount (m) required before runoff from exposed banks
!   runoff_coef    [float]  conversion of rainfall to runoff in exposed lake banks
!
!-------------------------------------------------------------------------------
&meteorology
   met_sw      = .true.
   lw_type     = 'LW_CC'
   rain_sw     = .false.
!   snow_sw     = .true.
   atm_stab    = .false.
   catchrain    = .false.
   rad_mode     = 1
   albedo_mode = 1
   cloud_mode   = 1
   fetch_mode   = 0
   !-- BC file details
   meteo_fl     = 'Meteo.csv'
   subdaily = .true.
   wind_factor = 0.9
   sw_factor = 1
   lw_factor = 1
  at_factor = 1.0
  rh_factor = 1.0
  rain_factor = 1.0
   cd          = 0.0013
   ce          = 0.0013
   ch          = 0.0013
   rain_threshold = 0.01
   runoff_coef    = 0.3
!  time_fmt = 'YYYY-MM-DD hh:mm:ss'
```

Figure 11. Meteorological parameters used

Configuration of Water Inflows into the Reservoir

To define water inflows, the user must specify the number of inflow sources (e.g., rivers) and their morphological characteristics. Each inflow is described by the following parameters:

Morphological Parameters

- **strmbd_slope**: Slope of the riverbed at the inflow point.
- **strm_hf_angle**: Half-angle of the riverbed cross-section (thalweg).
- **strmbd_drag**: Bed friction coefficient. Typical value: **0.016 ± 0.004**. In the case of pumped inflows (where friction is not applicable), this parameter instead defines the **height above the bottom** at which the inflow is introduced.

- **coef_inf_entrain**: Entrainment coefficient. If set to **0**, the model will compute entrainment dynamically. A constant value can be specified if needed for simplified modelling.

Inflow Data Files

The user must provide: the **names of the input files** containing inflow data, the **number of variables** included in each file and the **list of variables** (FLOW: Inflow discharge (m^3/s), TEMP: Inflow temperature (°C), and SALT: Inflow salinity (g/L or PSU)).

These inputs are essential for accurately simulating the thermal and hydrodynamic behaviour of the reservoir.

```
!-------------------------------------------------------------------------------
! inflows
!-------------------------------------------------------------------------------
!
!  num_inflows       [integer]   number of inflowing streams (0+)
!  names_of_strms    [string]    names of streams (comma separated list)
!  strm_hf_angle     [float]     stream half angle (degrees)
!  strmbd_slope      [float]     streambed slope (degrees)
!  strmbd_drag       [float]     streambed drag coefficient (-)
!  inflow_factor     [float]     inflow flow rate multiplier (-)
!  inflow_fl         [string]    inflow data filename(s) (comma separated list)
!  inflow_varnum     [integer]   number of columns (excluding date) to be read
!  inflow_vars       [string]    variable names of inflow file columns
!                                This should be a comma separated list, and must
!                                include FLOW, SALT & TEMP (for GLM), and
!                                optionally can include FABM var names.
! coef_inf_entrain   [real]      entrainment coefficient for inflows
!
!-------------------------------------------------------------------------------
&inflow
   num_inflows    = 2
   names_of_strms = 'Cize','Riseau'
   strm_hf_angle  = 70.0, 80.0
   strmbd_slope   = 0.075, 0.08
   strmbd_drag    = 0.016, 0.016
   inflow_factor  = 1.0, 1.0
   inflow_fl      = 'Inflow1.csv','Inflow2.csv'
   inflow_varnum  = 3,
   inflow_vars    = 'FLOW',
                    'TEMP',
                    'SALT',
   coef_inf_entrain = 0.
!  time_fmt = 'YYYY-MM-DD hh:mm:ss'
/
```

Figure 12. Setting up inflows for Allement

Configuration of Water Outflows from the Reservoir

To define outflows, the user must specify the following parameters:

- **Number of outflow structures**: Indicate how many water outlets (e.g., turbines, spillways, bottom outlets) are present.
- **Vertical position of each outlet**: Specify the depth or elevation at which each outflow is located within the water column. This is critical for accurately modelling thermal and density-driven flows.
- **Reservoir geometry at the outflow elevation**:
    - **Width** of the reservoir at the outflow level
    - **Length** of the reservoir at the outflow level

These geometric parameters influence the hydraulic behaviour and mixing processes near the outlet.

- **Outflow data file**: The output file must be provided in **CSV format** (e.g., Outflow.csv), containing time series data for each outlet.

```
!-------------------------------------------------------------------------------
! outflows
!-------------------------------------------------------------------------------
!
!  num_outlet      [integer]  no. of outlets
!  flt_off_sw      [bool]     floating offtake switches
!  outl_elvs       [float]    outlet elevations (comma separated list)
!  bsn_len_outl    [float]    basin length at outlets (m)
!  bsn_wid_outl    [float]    basin width at outlets (m)
!  outflow_fl      [string]   outflow data file
!  outflow_factor  [float]    outflow flow rate multiplier (-)
!  seepage         [bool]     do seepage processing [default is off - ie no seepage]
!  seepage_rate    [float]    seepage rate of water (m/day) from bottom layer
!
!-------------------------------------------------------------------------------
&outflow
   num_outlet   = 1
   flt_off_sw   = .false.
   outl_elvs    = 262.3,259.5
   bsn_len_outl = 1000
   bsn_wid_outl = 100
   outflow_fl   = 'Outflow.csv'
   outflow_factor = 1
   seepage  = .false.
   seepage_rate   = 0.0
  ! crest_width = 3
 !  crest_factor = 0.62
/
```

Figure 13. Example of water outlet settings

The Allement reservoir is characterized by a lower intake-to-water column height ratio compared to the Cize-Bolozon reservoir. Specifically, the intake at Allement is positioned at a depth of 10 meters within a total water column of approximately 20 meters, resulting in a ratio of 0.5. In contrast, the intake at Cize-Bolozon is also located at 10 meters, but the total water column is only about 15 meters deep, yielding a higher ratio of roughly 0.67. While the 1D model architecture used for both reservoirs accurately represent their respective morphologies and storage capacities, the key structural difference between the two lies in this intake-to-depth ratio. This distinction influences how water is withdrawn from each reservoir and affects the thermal stratification and mixing dynamics within the water column.

1.3.1.3 3D hydrodynamic model

Presentation of the software

We opted for a 3D description of the thermal and biogeochemical structures of the lake to account for the exchanges between the lake, its watershed and multiple inlets and outlets (Müller et al., 2018; USBR, 1993). We used an open source software (Delft3D) that has already been used in various lakes worldwide for hydrodynamic (Chanudet et al., 2012; Guénand et al., 2020; Soulignac et al., 2017). Delft3D is a fully 3D hydrodynamic modelling suite designed for simulating complex water systems such as rivers, estuaries, and coastal zones. It requires detailed spatial input, including high-resolution bathymetry, curvilinear or unstructured grids, and multiple boundary conditions (e.g., tides, river inflows, meteorological forcing). The model setup involves configuring numerous files for hydrodynamics, temperature, salinity, sediment, and potentially water quality. Its strength lies in resolving spatially and temporally variable flow fields and stratification in complex geometries, making it ideal for detailed engineering and environmental studies.

Our simulations ran with the software Delft3d-Flow v.4.02.03. The hydrodynamic model solves the Navier-Stokes equations for an incompressible fluid under the shallow water assumptions. The computational grid uses orthogonal curvilinear Cartesian coordinates.

Model setup for hydrodynamic

To set up a Delft3D-FLOW model for studying the hydrodynamics and stratification of a hydropower reservoir, the process begins with generating a high-resolution horizontal grid that conforms to the reservoir's shape, using a curvilinear or unstructured mesh. The vertical structure is crucial for capturing stratification, so sigma layers are employed—typically 10 to 20 layers depending on the depth and expected thermal gradients. Accurate bathymetric data is interpolated onto the grid, ensuring that key features like dam structures, intakes, and spillways are well represented. Boundary conditions are defined using time series data: upstream inflows include discharge, temperature, and possibly salinity, while downstream outflows reflect controlled releases through turbines or spillways. Meteorological forcing—such as wind, air temperature, solar radiation, and precipitation—is incorporated to drive surface heat exchange, which is essential for simulating stratification. Initial conditions include water levels and vertical profiles of temperature (and salinity if relevant), either from observations or assumed based on seasonal patterns. The model uses a turbulence closure scheme like k-ε to simulate vertical mixing, and density-driven flow is activated to account for stratification effects. Surface heat fluxes are modelled using bulk aerodynamic or Penman methods. Output settings are configured to capture water levels, 3D velocity fields, temperature and salinity distributions, and mixing coefficients. Calibration involves adjusting parameters like bottom roughness and turbulence settings to match observed water levels and temperature profiles, while validation uses independent datasets to ensure model reliability. This setup enables detailed analysis of flow dynamics, thermal layering, and the influence of hydropower operations on reservoir stratification.

3D hydrodynamic mesh

Bathymetric data is fundamental in constructing the hydrodynamic grid of the model. The grid is designed to replicate the morphological characteristics of the reservoir as accurately as possible while optimizing computational efficiency. Achieving a balance between horizontal and vertical resolution is essential to ensure both the stability of the hydraulic equations and the accuracy of the simulations.

The Saut Mortier reservoir is characterized by a long and narrow profile (Figure 13). It can be divided into three distinct zones, each with unique morphological features and sensitivities. The first zone lies at the confluence between the Saut Mortier inflow and the main body of the reservoir, where thermal stratification is expected to be most sensitive. The central section of the Coiselet reservoir is broader and features relatively uniform bathymetry with gentle slopes. In contrast, the downstream section is notably narrow, with steep slopes from the banks to the reservoir bed.

A two-dimensional computational grid was generated to accurately delineate the reservoir's surface domain, with spatial discretization optimized to preserve critical bathymetric gradients and morphological features essential for hydrodynamic fidelity. This grid was then combined with the bathymetric data to generate a 3D mesh, which serves as the hydrodynamic framework for the model.

Both reservoirs were integrated into a single Delft3D-FLOW model to allow for hydraulic and thermal exchanges between them. Delft3D-FLOW supports the use of "connectors" between separate water bodies, which can simulate conduits or tunnels enabling bidirectional flow—such as those found in pumped-storage hydropower systems. This setup allows for the simulation of water transfers between the upstream and downstream reservoirs, including turbine and pump operations. Once the grid is defined, the locations of tributary inflows and observation points—where output data will be extracted—are added to complete the model configuration.

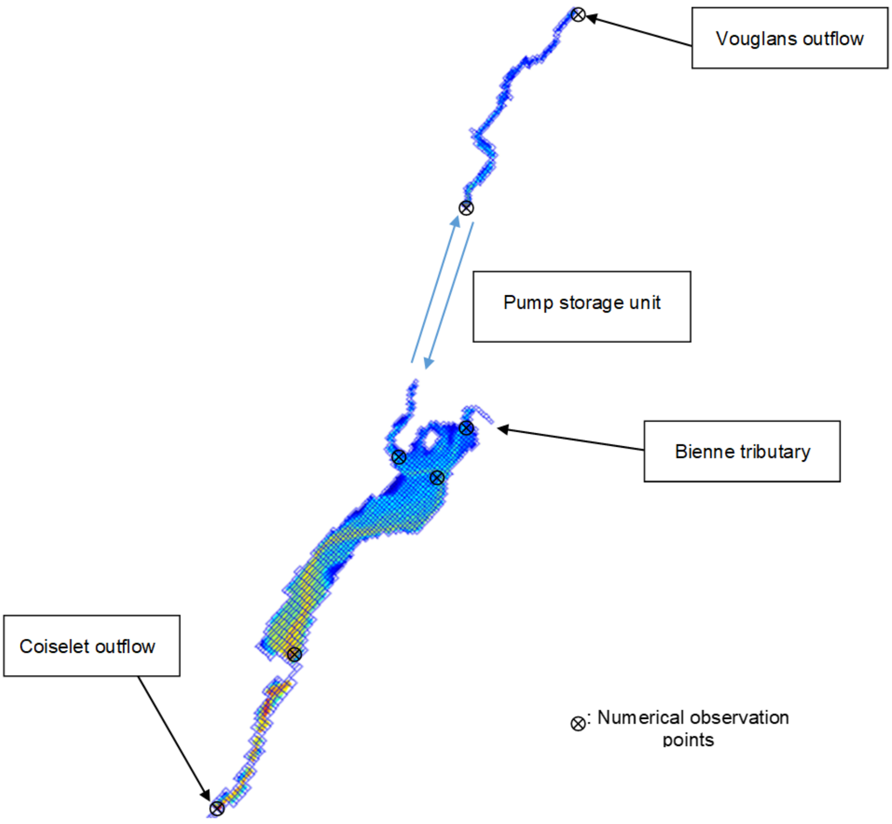

Figure 14. 3D model architecture

The horizontal grid was ~20 m and the vertical resolution was set to 2 m with a temporal resolution of 1 hour. We used a k-ε turbulence closure model to parametrize sub-grid processes. Heat exchange at the free surface was modelled by taking into account the separate effects of solar (short wave) and atmospheric (long wave) radiations, together with heat loss due to back radiation, evaporation and convection (Deltares, 2016). The Secchi depth input was set to be time constant.

1.3.2 Data & Scenarios

1.3.2.1 Water quality measurement network

A network of temperature sensors (Figure 15) has been set up to provide a robust and relevant dataset for calibrating the hydrodynamic models. This monitoring system was launched in 2019, then strengthened by verticals profiles in 2021 and 2022 following preliminary sensitivity analyses, which have highlighted the importance of the temporal and spatial resolution of the measurements for representing thermal phenomena in the reservoir.

The main reservoirs Vouglans, Saut Mortier, Coiselet, Allement, and Bolzons, are recorded by multi-parameter stations (SMP) and temperature measurement locations (T°C). In addition, key monitoring points include Pont de Jeurre, Pont de Poite, Pont d'Ain, and Pont de Chazey, strategically distributed along the river system are also monitored in order to inform on both tributary and downstream thermal dynamic.

This network provides comprehensive spatial coverage of the Ain reservoir chain, enabling detailed monitoring of thermal and water quality dynamics essential for model validation and environmental management.

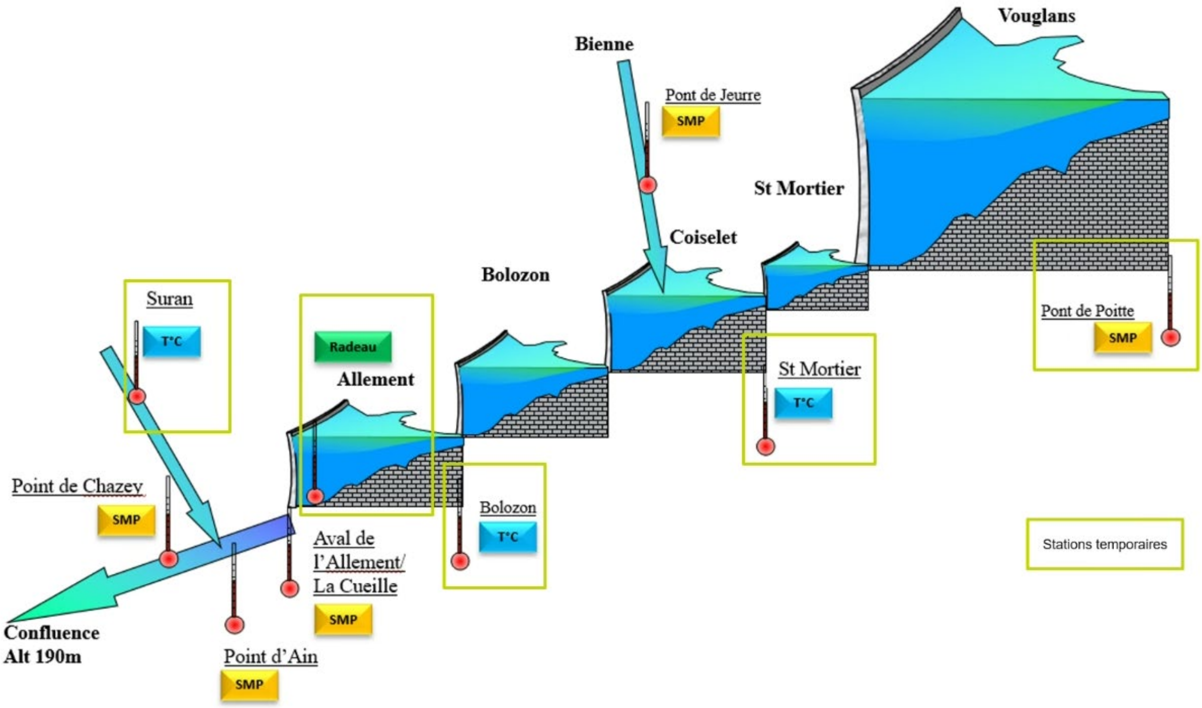

Figure 15. Water quality measurement network of the Ain reservoir cascade

1.3.2.2 Input data for the models

Input data, also known as forcing data, is one of the most sensitive elements in this type of hydrodynamic study. They directly affect the model's ability to faithfully reproduce the physical processes observed in the natural environment. These data generally include hydrological inputs (flows, water levels), meteorological conditions (air temperature, wind, humidity, radiation), and the thermal or physio-chemical characteristics of the incoming water. Any uncertainty or inaccuracy in these data can have a significant impact on the simulation results, particularly on the representation of thermal stratification, vertical exchanges or circulation dynamics. It is therefore essential to select, correct and adapt these data rigorously, in particular by using methods such as debiasing or recalibration based on local measurements.

1.3.2.2.1 Meteorological data

The nearest Météo-France station to the Allement site is the Ambérieu station, located approximately 20 km from the reservoir. In addition, for a precedent study, a local weather station was temporarily installed on a floating platform near the Allement dam (referred to as the *in situ* station) during the summer of 2013. Similar work has been reproduced by installing a weather station on the banks of the Coiselet reservoir in the summer of 2022. Given the similar elevation between the Ambérieu station and the reservoir, atmospheric pressure data from Météo-France were used directly without adjustment. However, for other meteorological variables, such as wind speed, air temperature, and humidity—which are more sensitive to local microclimatic conditions—correlation analyses were performed between the *in situ* and Météo-France datasets. Transfer functions were then applied to the Météo-France data to extend the time series over the full study period.

1.3.2.2.2 Inflow temperature

The temperature of inflows is a key forcing parameter for hydrodynamic models. In this study, two main inflows are considered: the Vouglans reservoir and the Bienne River. These inputs are used to drive the 3D model, while the inflow temperatures for the 1D models will be derived from the results of the 3D simulations. Although water temperature is monitored at the outlet of the Vouglans reservoir, the measurements exhibit significant biases, with daily variations reaching up to 15°C. These discrepancies suggest that the sensor is located downstream of the dam, in a shallow area that is highly sensitive to atmospheric heating and solar radiation, especially in the absence of active releases. However, based on in-lake temperature measurements, it is possible to reconstruct an annual time series of water temperature at the dam intake level, which more accurately reflects the thermal characteristics of the outflow. This reconstructed series captures the observed minimum and maximum temperatures within the reservoir and serves as a more reliable input for the model.

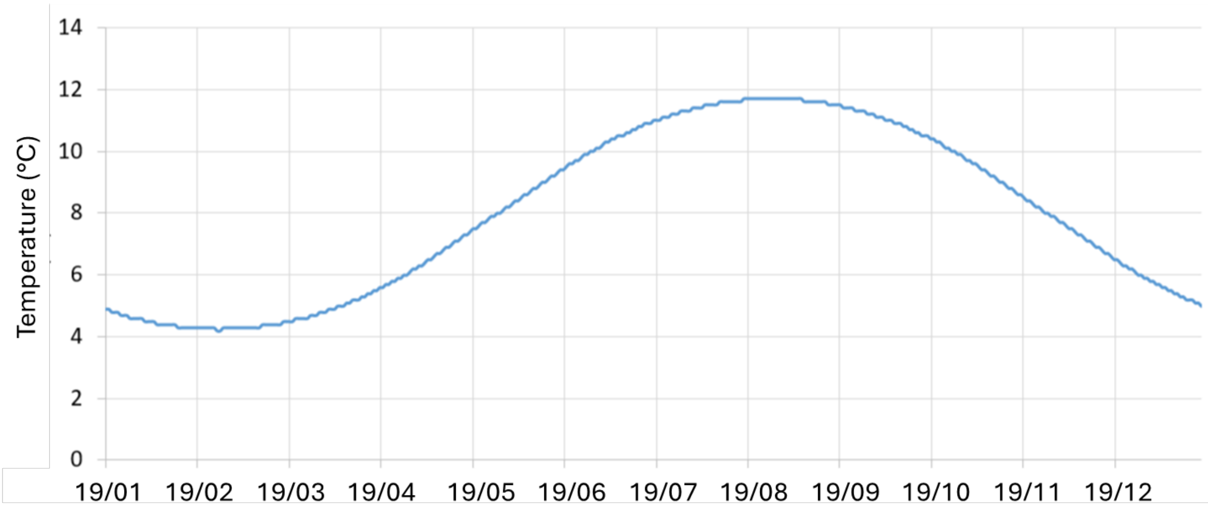

Figure 16. Input data: temperature of inflow - Saut Mortier

Temperature measurements were also conducted in the Bienne River, specifically at the Pont de Jeurre station, located northeast of the Coiselet reservoir. However, the dataset is incomplete, and the time series had to be reconstructed to support model inputs. The year 2019 was selected as the reference year for model development due to the availability of discharge and water level data, which are essential for establishing a water balance. The following figure presents the water temperature data recorded at Pont de Jeurre during 2019 and 2020. Winter temperature data are missing from this series. To address this gap, measurements taken downstream of the Vouglans reservoir were used as a proxy, as they reliably reflect the thermal behaviour of a river exposed to atmospheric conditions. Given that the Bienne River is more open and subject to stronger wind influence, which enhances heat exchange with the atmosphere, a correction factor of 0.9 was applied to the winter temperature values to account for the expected cooling effect.

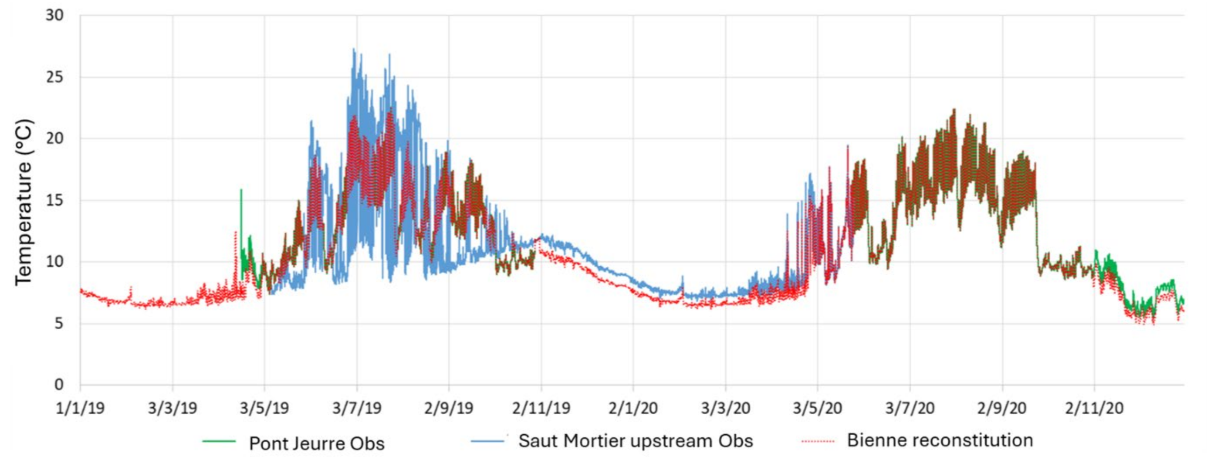

Figure 17. Reconstitution of the water temperature of the Bienne River

The chosen methodology enabled the reconstruction of a complete water temperature dataset for the Bienne River, prioritizing the use of measured data from locations near the study area. Although these reconstructed temperatures correspond to the specific hydrological and meteorological conditions of 2019, they were applied across all simulation scenarios. This decision is justified by the relatively minor thermal contribution of the Bienne compared to the dominant inflows from the Vouglans reservoir. A sensitivity analysis was conducted to assess the influence of this parameter on thermal stratification within the Coiselet reservoir and on downstream water temperatures. The results confirmed that the impact of the Bienne's thermal input remains limited under the modelled conditions.

1.3.2.2.3 Hydrology 2040 and hydropower management: Wet - Normal – Dry scenarios

As a first approach, meteorological data from the year 2006 were selected as the reference dataset, primarily because the summer period featured a significant number of days with average air temperatures exceeding 25°C—conditions that are representative of future climate scenarios projected for the 2040 horizon. To align these historical data with future climate projections, a statistical bias correction was applied based on the CMIP5 RCP8.5 scenario, enabling the generation of adjusted meteorological time series. Subsequently, hydrological data were translated into theoretical water management scenarios for 2040 using socio-economic models that incorporate assumptions related to water resource management and energy pricing.

Different methods of managing the structures were studied using three scenarios that reproduce conditions similar to a typical year: wet, dry and normal. Data on flows released from the Coiselet dam, in the absence of a PS between the Coiselet and Saut Mortier reservoirs. The integration of this new structure means that water resources can be managed differently. The flow and timing at the Coiselet outlet is therefore no longer the same with and without the STEP, with an increase in outflows in July and August. These scenarios provide a consistent framework for simulating future reservoir operations under evolving climatic and economic conditions.

2 Validation of 2021-2022 and 2023 model results

This study aims to explore the thermal dynamics of the Ain River along the cascade of hydraulic structures located between the Saut Mortier and Allement reservoirs, using an innovative combination of one-dimensional (1D) and three-dimensional (3D) hydrodynamic models. To validate the simulation results, the years 2021 and 2022 were partially modelled using field data collected through the deployment of temperature probes in the Vouglans and Coiselet reservoirs. Additionally, a local weather station was installed near the reservoirs in August 2022 to improve the representativeness of the meteorological forcing data. The modelling outputs were then compared with in situ measurements to assess the accuracy of the simulations and, if necessary, to calibrate or adjust the models for improved performance.

2.1 Vouglans reservoir

The initial step in the modelling process involves validating the hydraulic balance, with particular attention to the accuracy of water level fluctuations (tidal range) within the reservoir. The simulation results demonstrate a high level of agreement with observed data, indicating that the model accurately captures the reservoir's usable storage volume. The differences between measured and simulated water levels are minimal (<0.1m), confirming the model's ability to represent the hydrodynamic behaviour of the system with precision.

The simulated thermal stratification of the Vouglans reservoir (Figure 17) is illustrated in a simplified manner in the Figure 18, with representative average temperature values assigned to each 5-meter depth layer—corresponding to the vertical resolution used in the Vouglans 3D model. A comparison with observational data highlights the model's ability to accurately reproduce the annual cycle of thermal stratification. During the winter period (October to March), the water column remains largely homogeneous in temperature. As air temperatures rise and solar radiation increases in spring, surface layers begin to warm, initiating the development of a thermal gradient. This stratification intensifies throughout the summer months. In 2021, the thermocline was positioned slightly above the 10-meter depth mark, while in 2022 it extended deeper, reaching approximately 15 meters. This shift is attributed to warmer and drier meteorological and hydrological conditions observed that year.

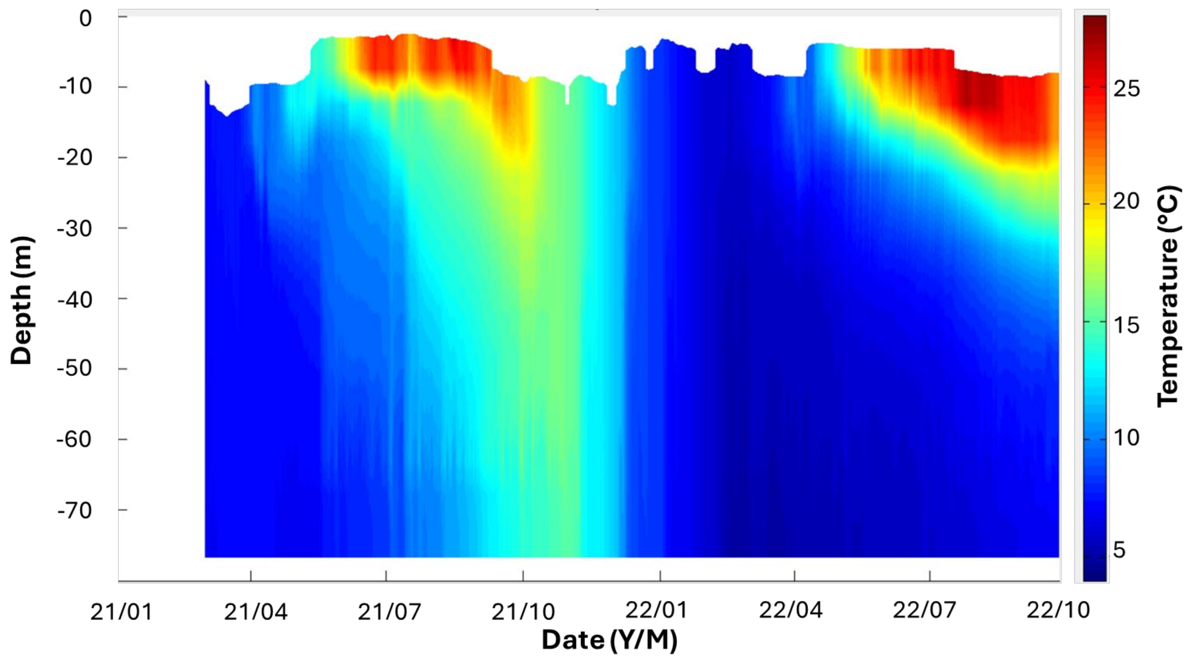

Figure 18. Simulated thermal stratification - Vouglans Dam: 2021-2022

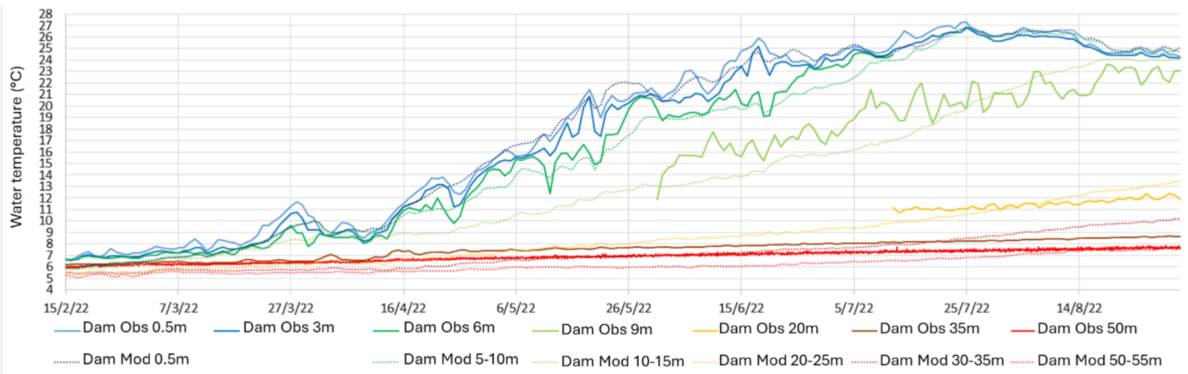

Figure 19. Comparison of measured and modelled thermal profiles – Vouglans Dam 2022

The model accurately reproduces surface water temperatures, particularly within the upper 10 meters of the water column—a zone highly sensitive to atmospheric forcing such as air temperature, wind, and solar radiation. In this layer, the temperature difference between observed and simulated values remains minimal, typically within 0.5°C. From July onward, surface temperatures become more uniform due to the deepening of the thermocline. At greater depths—specifically between 20–35 meters and around 50 meters—the simulated temperature profiles closely align with observations, with deviations generally within ±1°C. These results confirm the model's ability to reliably capture both the structure and seasonal evolution of thermal stratification in the Vouglans reservoir. Furthermore, the model effectively represents temporal variations in stratification intensity and depth (Table 1).

Table 1. Validation statistics of Vouglans model

STATION	DEPTH (MOD VS OBS)	RSQUARED	NSE	BIAS
VOUGLANS	0_5m_vs_3m	0.54	0.51	-0.17
VOUGLANS	10_15m_vs_9m	0.86	0.83	0.44
VOUGLANS	15_20m_vs_15m	0.79	0.72	0.46
VOUGLANS	30_35m_vs_30m	0.81	0.63	0.3
VOUGLANS	40_45m_vs_45m	0.76	0.47	-0.17

Based on these results, the reservoir can be confirmed as a significant cold-water source. Throughout both winter and summer of 2022, water temperatures below 30 meters remained consistently below 13°C. This persistent cold layer ensures a reliable supply of cool water to downstream reservoirs, including Saut Mortier and Coiselet, which is critical for maintaining thermal regimes and supporting ecological and operational objectives.

Figure 20. The Vouglans reservoir and dam

2.2 Coiselet reservoir

The Coiselet reservoir experiences very limited water level fluctuations, which allows the model to accurately reproduce its slight variations—typically within a range of just a few tens of centimetres. In contrast, the Saut-Mortier reservoir has a narrow morphology with steep banks and a very short water residence time. These characteristics are more challenging to simulate, particularly given that the horizontal resolution of the hydrodynamic grid was primarily optimized for the Coiselet reservoir, which has a significantly different surface area and morphology. Despite these constraints, the model performs well during the summer period, successfully capturing the water level fluctuations in the Saut-Mortier reservoir with only minimal relative error.

The Figure 19 provides a comparative analysis of measured and simulated water temperatures at various depths in the Coiselet reservoir from May to August 2023. It includes observed data at 3 m and 6 m depths (solid lines) and simulated temperatures at 3 m, 5 m, and 6 m (dotted lines).

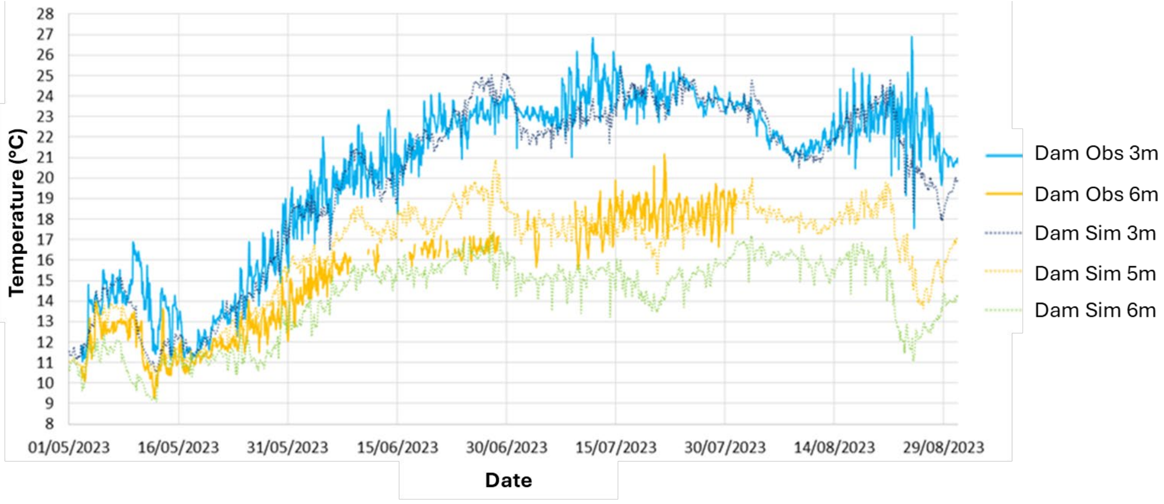

Figure 21. Comparison of measured and modelled thermal profiles - Coiselet 2023

The quality of the stratification simulation appears to be reasonably good, as the simulated temperature profiles generally follow the seasonal trends and thermal dynamics observed in the measurements. At 3 meters, the simulated temperatures (dotted blue) closely track the measured values (solid blue), with only minor deviations, indicating a good representation of surface-layer dynamics. At 6 meters, the simulated data (dotted green) also align fairly welling with the observed values (solid yellow), particularly during periods of rapid thermal transitions (Table 2). The inclusion of a 5-meter simulation (dotted orange) provides additional insight into the vertical gradient and highlight the vertical sensibility of temperature gradient simulation.

Table 2. Validation statistics of Coiselet model

STATION	DEPTH (MOD VS OBS)	RSQUARED	NSE	BIAS
COISELET	3m_vs_3m	0.92	0.91	-0.45
COISELET	6m_vs_5m	0.82	0.79	0.47
COISELET	6m_vs_6m	0.78	0.43	-1.62

Overall, the model captures the onset and persistence of thermal stratification effectively, with acceptable deviations that remain within a realistic range. These results suggest that the model is well-calibrated for simulating vertical thermal structure, though slight refinements could improve accuracy during transitional periods.

2.3 Cize-Bolozon and Allement reservoirs

The water temperature data used in the 1D modelling of the Cize-Bolozon reservoir are derived from the 3D thermal simulation of the Coiselet reservoir outlet. At this stage of the modelling process, the flow rates are assumed to be equal to those at the Coiselet outflow. The Cize-Bolozon and Allement reservoirs are not modelled with water level fluctuations, a choice justified by their small storage volumes and the very short residence time of water within them. Additionally, the lack of temperature data for minor tributaries—whose thermal contributions are negligible—supports this simplification. The water temperature used as input for the Allement reservoir is obtained following the simulation of thermal behaviour in the Cize-Bolozon reservoir. Only after both reservoirs have been simulated can the modelled water temperature be compared with measurements taken downstream of the Allement dam, allowing for validation and potential calibration of the model.

The Figure 22 presents a comparison between measured and simulated water temperatures at various depths in the reservoir from May 1 to August 29, 2023. The graph includes observed temperatures at 0.5 m, 6 m, and near the bottom (fond), as well as simulated temperatures at 1 m, 6 m, and bottom layers.

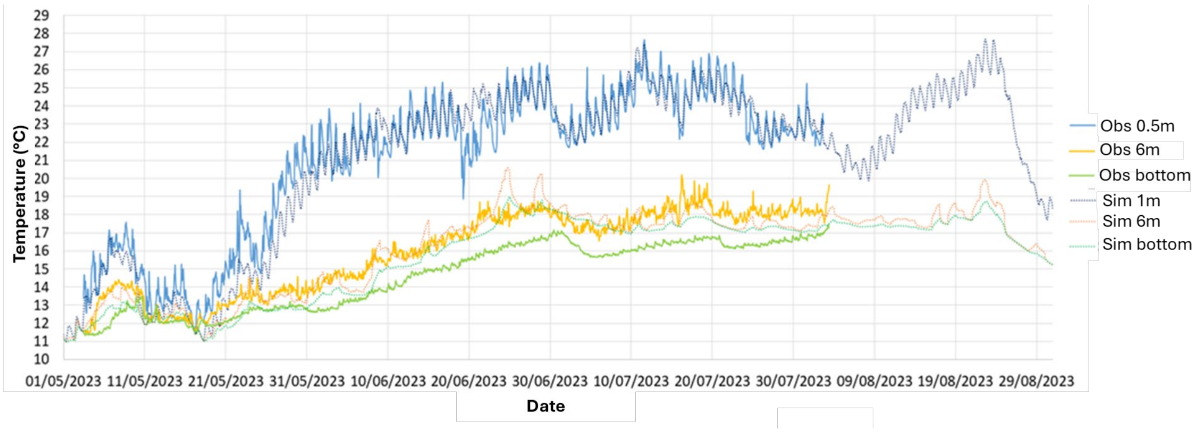

Figure 22. Comparison of measured and modelled thermal profiles - Cize-Bolozon 2023

The model shows a good overall agreement with the observed data, particularly in capturing the seasonal warming trend and the development of thermal stratification (Table 3). The simulated temperature at 6 meters (orange dashed line) closely follows the measured values at the same depth (yellow line), with only minor deviations. Similarly, the bottom-layer simulation (green dashed line) aligns well with the measured bottom temperatures (solid green line), indicating that the model accurately represents the persistence of cooler water at depth.

Table 3. Validation statistics of Cize-Bolozon model

STATION	DEPTH (MOD VS OBS)	RSQUARED	NSE	BIAS
CIZE	1m_vs_1m	0.95	0.93	-0.22
CIZE	6m_vs_6m	0.92	0.9	-0.14
CIZE	Bott_vs_Bott	0.95	0.72	0.74

At the surface, the simulated temperature at 1 meter (red dashed line) tracks the general trend of the 0.5 m measurements (blue line), although some discrepancies are visible during periods of rapid warming or cooling, likely due to short-term atmospheric variability not fully captured by the model.

Overall, the simulation effectively reproduces the vertical thermal structure and its evolution over the summer period, confirming the model's ability to represent both surface dynamics and deeper thermal stability in the Cize Bolozon reach.

The Figure 23 presents a comparison between measured and simulated water temperatures at the upstream section of the Allement dam, covering the period from May 1 to August 29, 2023. It includes surface and bottom temperature profiles, both observed and modelled. The measured surface temperatures (red line) show significant variability and reach peak values close to 30°C during the summer, reflecting strong atmospheric influence. In contrast, the measured bottom temperatures (blue line) remain relatively stable and cooler, ranging between 11°C and 15°C, indicating the presence of a persistent cold layer. The simulated surface temperatures (light blue line) follow the general trend of the observed data, capturing the seasonal warming pattern with reasonable accuracy, though some deviations are noted during peak heat periods. The simulated bottom temperatures (green line) align closely with the measured values, confirming the model's ability to reproduce the thermal stability of deeper layers. Overall, the figure demonstrates that the model effectively captures the vertical thermal structure and seasonal dynamics of the Allement reservoir.

Figure 23. Comparison of measured and modelled thermal profiles - Allement 2023

Table 4. Validation statistics of Allement model

STATION	DEPTH (MOD VS OBS)	RSQUARED	NSE	BIAS
ALLEMENT	Surf_vs_Surf	0.85	0.83	-0.28
ALLEMENT	Bott_vs_Bott	0.96	0.93	0.28

2.4 Ain hydropower downstream

Finally, the temperature data measured downstream of the Allement structure are compared with the output of the Allement model. To highlight the full range of simulation periods covered, graphs for the years 2021–2022 and 2023 are presented. Figure 22 presents a comparative analysis of water temperature data downstream of the Allement dam, spanning respectively from March 1, 2021, to August 23, 2022, and from March 15 to end of August 2023. It features two temperature profiles: the modelled temperature (depicted in red) and the observed temperature (in blue), both showing daily average values. The graph reveals a strong seasonal pattern in both datasets, with temperatures peaking during the summer months and dipping in winter, reflecting natural climatic cycles. Overall, the modelled temperature closely tracks the observed temperature, indicating a good agreement between simulation and reality. However, some discrepancies are evident. Minor deviations suggest areas where the model could be refined to better capture local thermal dynamics or account for environmental factors not fully represented in the simulation. Overall, the figures demonstrate a high level of correlation between the two datasets, supporting the reliability of the model while highlighting opportunities for further calibration (R^2=0.97, NSE=0.97, Bias=-0.15°C).

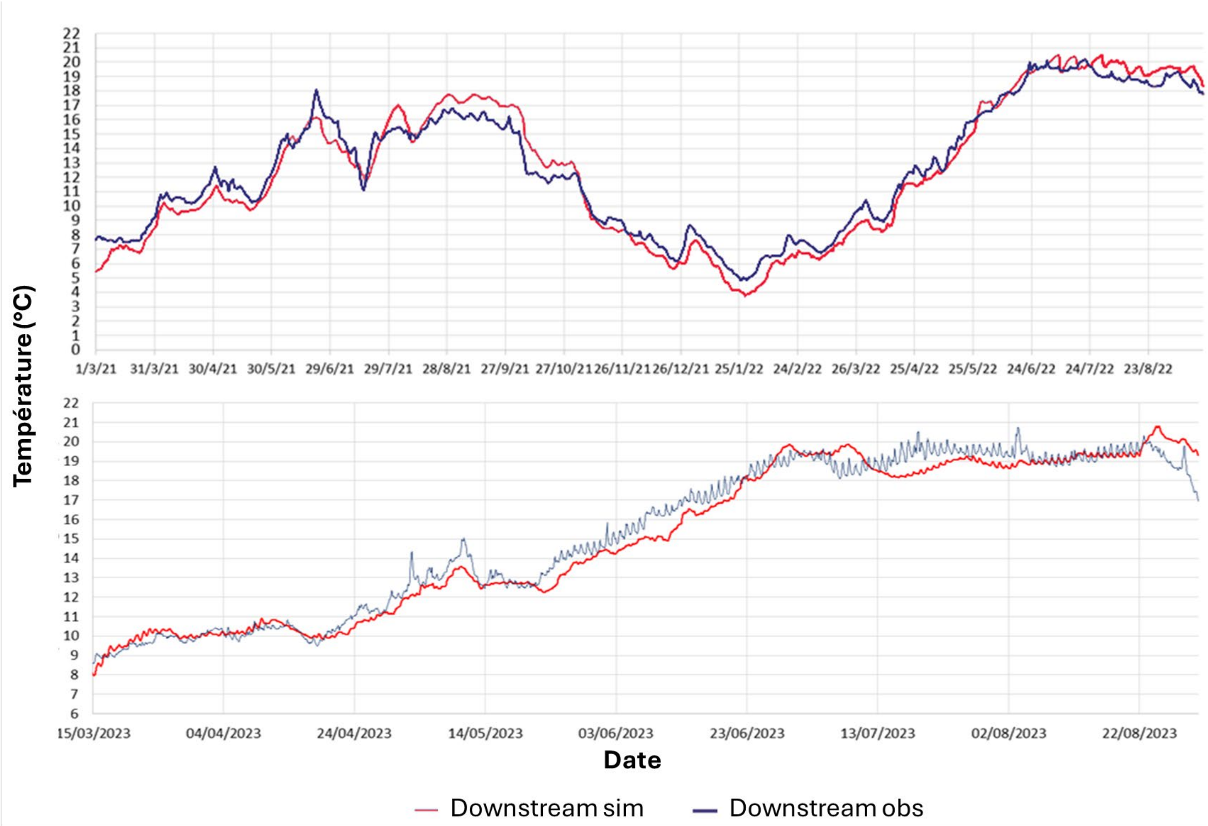

Figure 24. Comparison of measured and modelled thermal profiles - Downstream 2021-2022 and 2023

3 Results

3.1 Potential of pump storage retrofitting

The validated models are then used to run the 2040 management scenarios under 3 climates type (Wet, Normal and Dry). The main change can be seen at the Coiselet reservoir. The Figure 23 illustrates the impact of pump storage operations on the thermal structure of the Coiselet reservoir under three hydrological scenarios: Dry, Normal, and Wet. It consists of six thermal profile plots arranged in two rows—the top row shows conditions without pump storage, while the bottom row shows conditions with pump storage. Each column corresponds to a different hydrological condition, progressing from Dry on the left to Wet on the right. A colour gradient ranging from blue (0°C) to red (30°C) represents the temperature distribution within the reservoir.

Across all scenarios, the presence of pump storage clearly modifies the thermal profile. In Dry conditions, pump storage leads to a noticeably cooler surface layer and a more uniform vertical temperature distribution, indicating enhanced mixing. Under Normal conditions, the effect remains significant, with reduced surface temperatures and a shallower thermocline compared to the non-pump scenario. In Wet conditions, the differences are subtler, but pump storage still contributes to slightly lower surface temperatures and diminished stratification. Overall, the figure demonstrates that pump storage operations play a key role in mitigating thermal stratification, especially during drier periods, thereby enhancing the reservoir's thermal resilience and supporting more adaptive water management strategies.

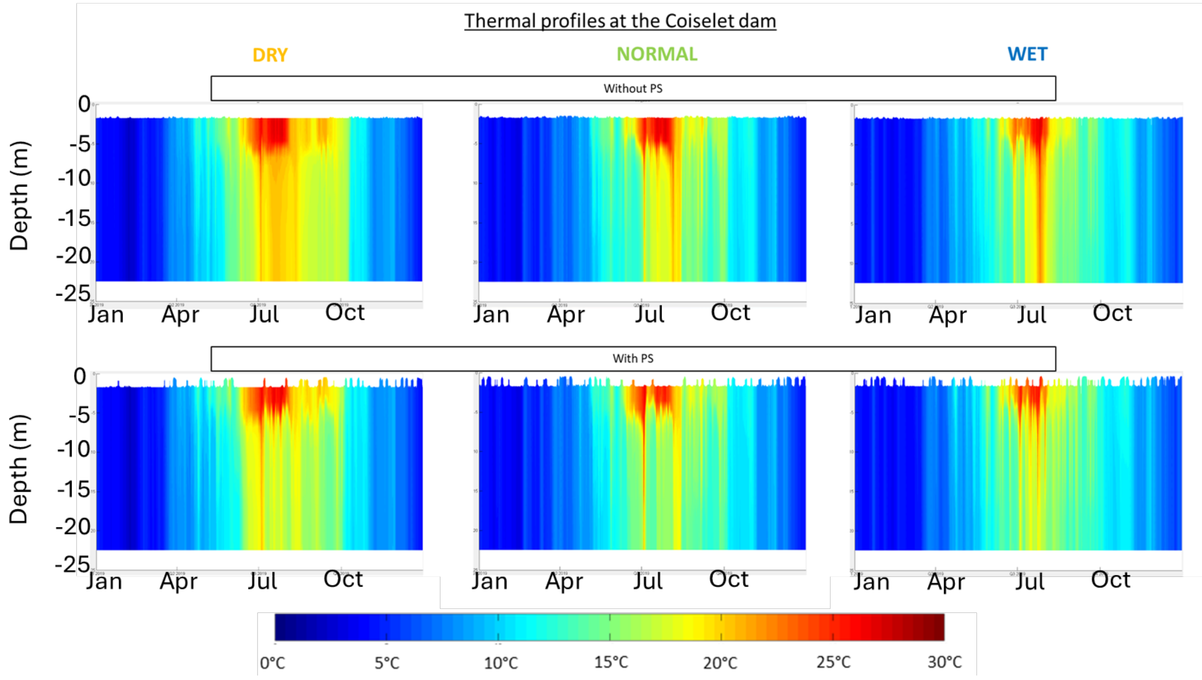

Figure 25. Thermal profiles at Coiselet dam - Horizon 2040 without PS vs. PS

The Table 5 summarizes the thermal behaviour of three downstream sites—Coiselet downstream, Cize-Bolozon downstream, and Allement downstream—under Dry, Normal, and Wet hydrological conditions, focusing on both yearly and summer mean water temperatures. The values in black represent the mean temperatures, while the blue values in brackets indicate the temperature reduction due to pump storage operations, and the red values show the Up-Down heat gain, which reflects the thermal increase along the river continuum.

Table 5. Modification of thermal behaviour by PS retrofitting - Ain River

	Reservoir	Dry	Normal	Wet
Yearly mean temperature (°C)	Coiselet down.	10.9 (-0.8)	10.1 (-0.6)	10.0 (-0.4)
	Cize-Bolozon down.	12.0 (-0.8)	10.8 (-0.5)	10.6 (-0.4)
	Allement down.	12.2 (-0.8)	11.1 (-0.7)	10.9 (-0.3)
	Up-Down gain	**1.3**	**1**	**0.9**
Summer mean temperature (°C)	Coiselet down.	10.9 (-0.8)	10.1 (-0.6)	10.0 (-0.4)
	Cize-Bolozon down.	12.0 (-0.8)	10.8 (-0.5)	10.6 (-0.4)
	Allement down.	12.2 (-0.8)	11.1 (-0.7)	10.9 (-0.3)
	Up-Down gain	**1.3**	**1**	**0.9**

*(theoretical thermic PS Gain)

Across all conditions, pump storage consistently reduces water temperature, with the cooling effect being more pronounced in summer (up to −1.8 °C). Yearly mean temperatures range from about 10.0 °C to 12.2 °C, with slightly higher values under dry conditions. The Up-Down heat gain remains stable at +1.0 °C annually, indicating a consistent thermal increase from upstream to downstream.

In summer, temperatures are significantly higher, especially under dry conditions, reaching up to 22.4 °C at Aval Allement. The Up-Down heat gain is also more substantial in summer, peaking at +3.9 °C in dry years, and decreasing to +2.4 °C and +2.5 °C in normal and wet years, respectively. This suggests that thermal accumulation is more intense during dry periods, likely due to lower flow rates and increased solar exposure.

4 Next steps

4.1 Identification of thermal management indicators

We aim to implement a robust and comprehensive methodology for optimizing reservoir management through a structured, multi-step process that includes simulation, scenario clustering, and chaining tests (Figure 24). The process begins with a simulation plan tailored to each reservoir, organized around a matrix defined by the range of upstream flow (Q_{up}) crossed with the range of upstream temperature (T_{up}). Each cell in this matrix represents a unique scenario, initialized from a distinct thermal state characterized by internal energy (IE), thermocline depth (Zth), and stratification strength (St). These simulations are run over a one-week period to capture short-term thermal dynamics under varying conditions.

The next phase involves analysing the simulation outputs through clustering based on thermal gain, which groups the scenarios into three distinct clusters. Each cluster represents a different management mode or thermal response profile. This classification helps identify patterns in system behaviour and supports the selection of optimal strategies. Visual representations of the clusters facilitate comparison, and from this analysis, we aim to identify key limnological thresholds that summarize the system's thermal resilience and provide actionable management indicators.

The final step is the chaining test, which integrates the clustered scenarios into a broader forecasting and decision-support framework. This includes hydrological forecasting for key reservoirs and the optimization of hydro-thermal operations with objectives such as minimizing support requirements, enhancing thermal resilience (e.g., through preparation time), and evaluating the impacts of climate change. The methodology incorporates CMIP5 hydro-climatic projections and aligns with EDF's Harmony 2030 and 2050 energy price scenarios, ensuring that the proposed strategies remain robust under future climatic and economic conditions. Altogether, this forward-looking approach supports resilient, adaptive, and efficient reservoir management in the face of evolving environmental and operational challenges.

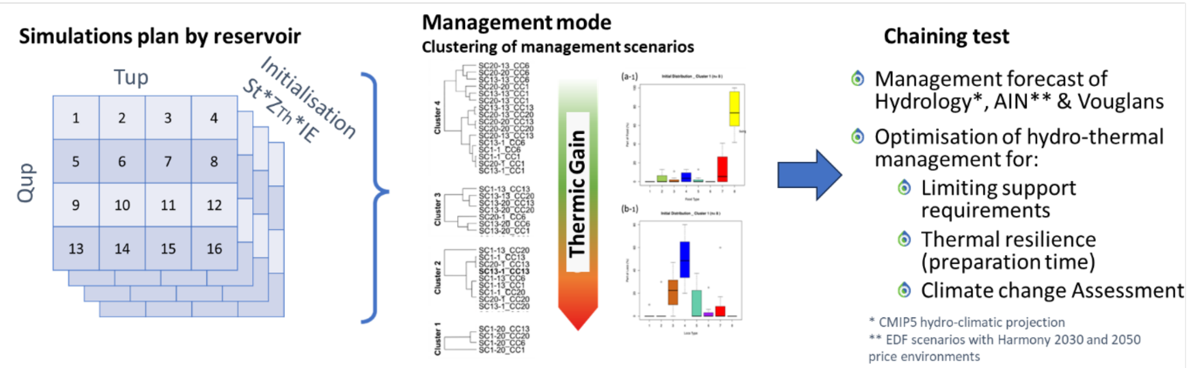

Figure 26. Identification of thermal management indicators

To support the implementation of our reservoir management methodology, we developed a semi-automated simulation tool specifically designed to handle the complexity and scale of multi-scenario modelling. This tool enables the efficient simulation of reservoir chains across a wide range of hydrological and thermal conditions, significantly reducing manual workload while ensuring consistency and reproducibility.

4.2 Implementation of hydrothermal river model

As part of our methodology, a key phase involved the development of a hydrothermal model designed to simulate the downstream thermal dynamics of the reservoir system. This model is essential for capturing the influence of hydroelectric operations on the thermal regime of the river and its potential ecological impacts. By integrating hydrological inputs with thermal processes, the model shall enable us to reproduce temperature profiles under various flow and management scenarios and provide relevant information for ecological model supported by task 4.3.

5 Conclusion

As part of our effort to improve the understanding and management of thermal dynamics in the Ain River basin, we enhanced and applied both 1D and 3D hydrothermal models previously developed by EDF's engineering centre. These models were initially used in the initial phase of impact assessment of the Mortier-Saut project and supported the design of retrofitting strategies for pumped storage operations. In this phase, we focused on testing their functionality and verifying the calibration of what represents the first version of a digital twin of the reservoir system. This work led to a significant advancement: the consolidation of all models into a fully 3D framework, allowing for a more accurate representation of spatial thermal processes and vertical stratification.

Building on this foundation, we are now qualifying the environmental sensitivity of each reservoir by analysing its limnological response to meteorological forcing and upstream flow-temperature conditions, in relation to its specific management mode. To support this, we developed a semi-automated simulation tool capable of running large scenario sets and linking multiple reservoirs dynamically. This tool enables us to explore a wide range of operational and climatic configurations efficiently.

In parallel, we have begun generating the first flow-temperature scenario series for the entire reservoir chain and initiated the development of a downstream river model. This model will extend the hydrothermal analysis beyond the reservoirs, enabling us to assess the ecological impacts of thermal regimes on downstream habitats.

This modelling framework not only strengthens the assessment of thermal resilience across the reservoir system but also provides a solid foundation for evaluating how different operational strategies influence ecological compartments downstream, including fish habitats and aquatic biodiversity. Beyond ecological analysis, this work opens new perspectives for achieving climate-resilient hydropower production by leveraging integrated hydro-thermal models and climate projections. These tools enable EDF to anticipate future hydrological and thermal conditions and to adapt operations accordingly—potentially even in near real-time—enhancing both environmental performance and operational flexibility. This integrated approach positions the Ain hydropower chain as a forward-looking model for sustainable river basin management under changing climate conditions.

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