HYDROEUROPE

REPORT 2
TEAM 1

VAR &
VESUBIE
CATCHMENT

01/03/2024

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Introduction

As discussed in our first report, the Mediterranean region is particularly vulnerable to flash floods, posing a significant threat to human safety and infrastructure. The Mediterranean Sea is bordered by high reliefs, located to the east of the Atlantic Ocean and to the north of one of the largest deserts in the world, which means that the climate of the Mediterranean basin is unique. The Alpes-Maritimes is subject to numerous storms due to its location between oceanic, desert and continental climates, all characterised by extreme climatic episodes ranging from heat waves to intense rain. Among them, the Mediterranean episodes are the most extreme due to the power and unpredictability of flooding phenomena, leading to flash floods. The storm phenomena that cause them mainly occur in autumn, when the atmosphere begins to cool while the sea is still warm.

For future climate projections, the Mediterranean region is especially interesting as several studies have reported a decrease in total annual rainfall. In terms of heavy precipitation events in the South of France, historical trends show an increase in their intensity, particularly since the 1980s. We will try to represent these phenomena in the hydraulic and hydrologic models.

At the end of the first week, one hydrologic model (HEC-HMS) and two hydraulic models (MIKE-11, TELEMAC) have been constructed, calibrated and validated for the Var catchment and Vésubie sub-catchment. In this report, the impact of climate change and increased urbanisation on the models and the future of flooding in the region will be explored.

Objectives

The main objective of this project is to evaluate the current and future hydraulic behaviour of the Saint-Martin-de-Vésubie area under flash flood conditions and identify an acceptable location to rebuild a wastewater treatment plant (WWTP). To do so, the impacts of climate change on the Var and Vésubie catchments are researched and three different future scenarios are created. Three 100-year return period precipitation events are run in the HEC-HMS model for rainfall-runoff modelling. The discharge results from the hydrologic model will be used to simulate fluid dynamics in 2D using TELEMAC (hydraulic model). These models are used to assess the impacts of flash flooding in the Var catchment in the future. From this, we can locate an optimum area for the construction of the new WWTP. The workflow for phase 2 of this project is seen in Figure 1. A different method was chosen to assess the impact of climate change using the 1D MIKE-11 model, which will be discussed in the MIKE-11 section of this report. The calibration results, sensitivity analyses and the discussion of the model uncertainties can be found in Report 1.

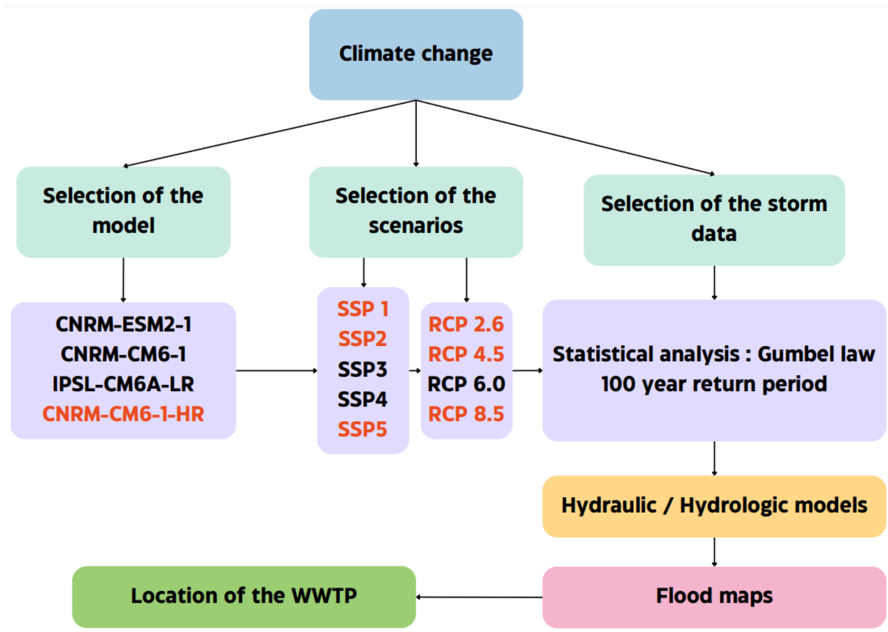


Figure 1: Organisational workflow for phase 2 of the project

Background

Predicted Climate Change Impacts on the Var Catchment

There are a few studies that have assessed the historical trend of increasing temperatures in the Var and Vésubie catchments. The following figures are the result of the most comprehensive study, which used data from 700 stations between 1958 and 2015 to assess historical changes in temperature and precipitation (Ribes et al., 2019).

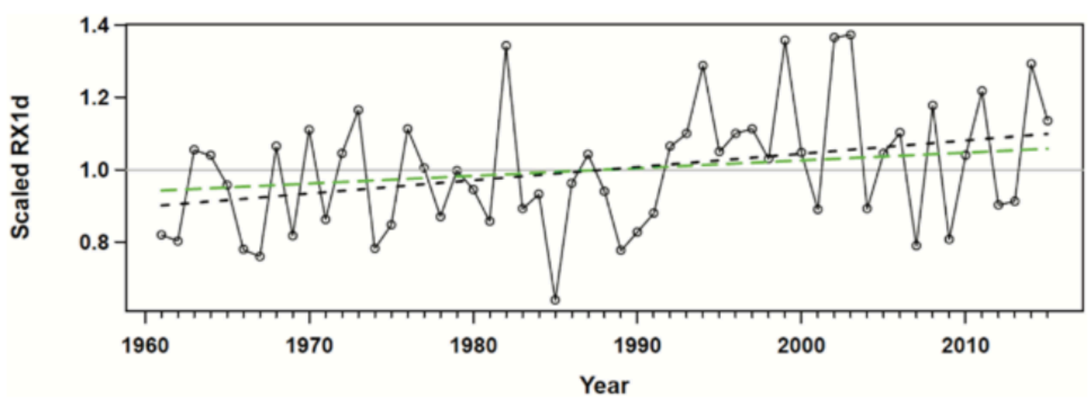


Figure 2: Times series of the regional indicator of the intensity of heavy precipitation events over the period 1961-2015 on the Mediterranean rim (Zugasti & Merad, 2022)

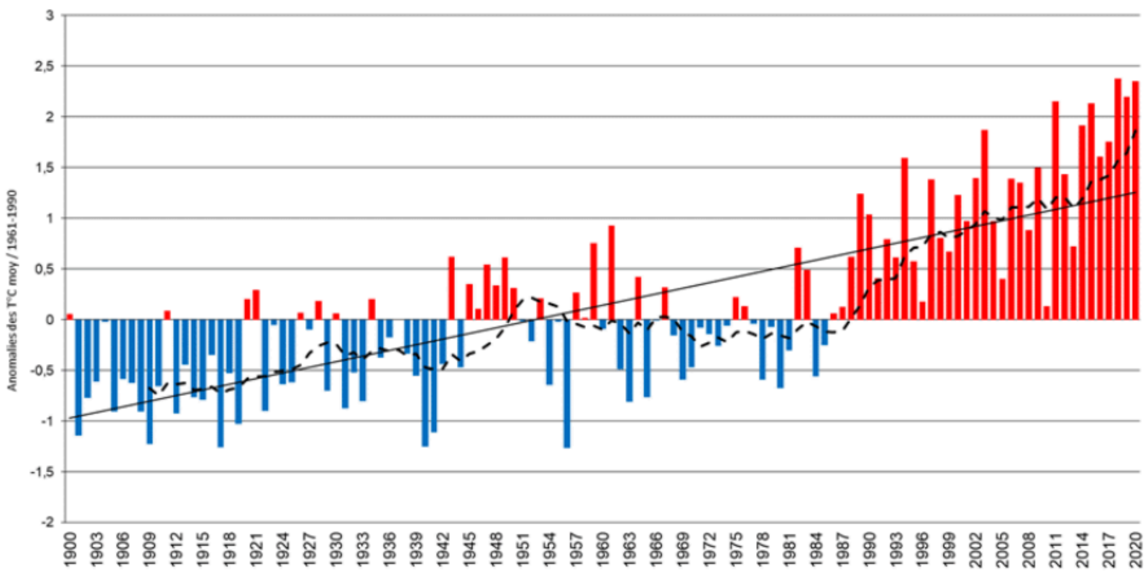


Figure 3: Evolution of the anomalies in temperature in the Alpes-Maritimes region between 1900 and 2020 from Météo France data (Zugasti & Merad, 2022)

Figure 2 shows a slight increase in the intensity of extreme precipitation events in the Mediterranean region. An increase in temperature anomalies can be seen in Figure 3, particularly since the 1980s. The three years which are respectively placed first, second and third on the scale of the hottest years compared to the average from 1961-1990 are 2018, 2019 and 2020. An average increase in the temperature anomalies of 2.1°C can be seen each year over the last 3 years.

Increasing air temperatures could reduce the amount of snow retained during the winter, increasing flows during this season. In addition, the quantity of melted snow from June to October would increase due to the increase in temperatures. This will increase the volume of water in rivers, particularly for rivers subject to glacial influence. On average, the temperature of the Alps has increased by 0.9 to 1.5°C since 1850, almost double the global average (Prudent-Richard et al., 2008).

Ghulami et al. (2022) also support these findings. A distributed MIKE SHE hydrological model was used to simulate several RCPs and evaluate the possible influences of climate change on the water resources in the Vesubie. Several Representative Concentration Pathways (RCP), which are projected greenhouse gas concentrations, were used to evaluate different future scenarios. The results indicated an increasing trend in temperature for the future (2031-2050) compared to the baseline (1986-2005) ranging from +0.8 to +2.1 °C under RCP4.5 and +1.3 to +2.3 °C under RCP8.5. Additionally, while a few months have a slight increase in precipitation, there is an overall decreasing trend in annual precipitation for the RCPs tested, as seen in Figure 4 below.

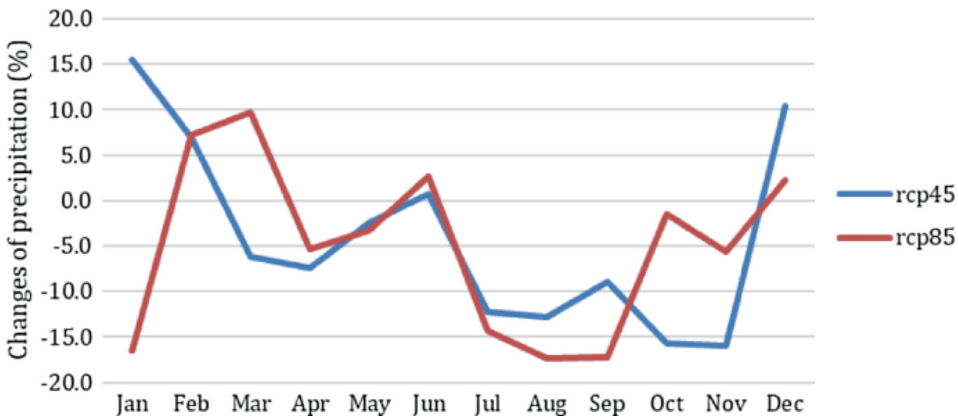


Figure 4: Predicted changes in precipitation for the Vésubie catchment in the period of (2031–2050) compared with the baseline of (1986–2005) (Ghulami et al., 2022)

Another study focusing on extreme precipitation found that heavy rainfall events are increasing in intensity in the Vesubie Valley. In the Mediterranean region, there has been a 22% increase in the annual maxima of daily accumulations between 1961 and 2015 (Ribes et al, 2019). Furthermore, extreme rainfall events, especially those exceeding 200 mm in 24 hours, were found to occur more frequently in the region (Gourbesville & Ghulami, 2023). Other analyses, including the 6th IPCC report, also found that there will be an intensification of heavy precipitation events. This is different from the Ghulami et al. (2022) study mentioned as it focused on all precipitation, not just extreme events. Overall, according to these studies, an intensification of extreme events and an overall decrease in total annual precipitation is expected in the future if predicted patterns of climate change persist.

A combination of factors that leads to a change of regime for torrential floods

Even if the models have difficulty predicting the evolution of rainfall totals in the Alps (a slight increase seems to be taking place), the real danger would be the evolution of rainfall regimes. Several hypotheses are suggested by Prudent-Richard et al. (2008):

"Models predict a decrease in summer precipitation and an increase in winter precipitation;
- Summer precipitation could occur with less frequency and in the form of more intense showers;
- Winter precipitation will occur more in the form of rain (rather than snow) and up to higher altitudes."

A rise in temperatures would lead to an increase in the share of liquid precipitation during the winter period and advancement of high flow rates is linked to the melting of the snow cover. The Alps will see a change in the seasonality, frequency and intensity of torrential floods.

The ARNICA project has catalogued 500 events since 1970 and highlighted the essential role played by climatic variables on a regional scale on the probability of occurrence of debris flows. In certain sequences, the increase in the number of debris flows is likely an effect of summer warming, which leads to more convective effects and thus more stormy episodes.

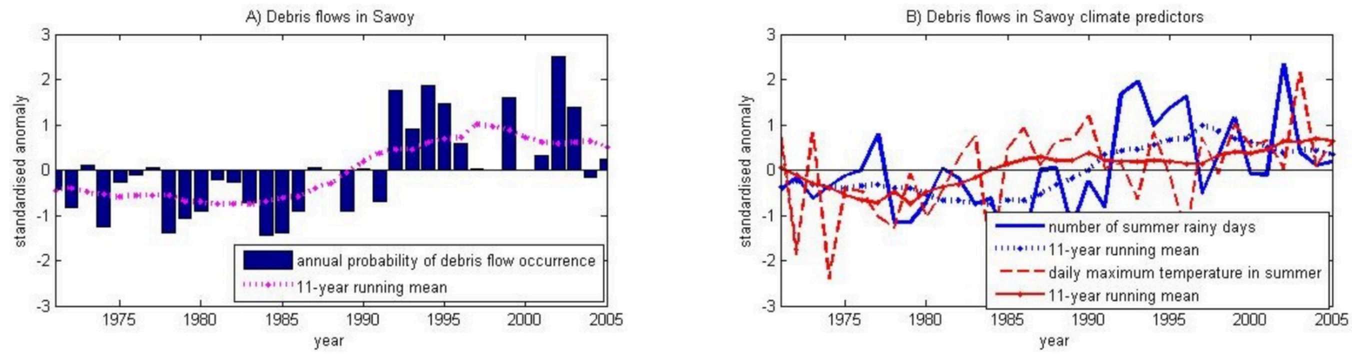


Figure 5: Response of hazard to recent changes in summer weather factors. (A) Annual frequency of debris flows in Savoie and (B) identified predictors (Einhorn et al., 2015)

Figure 5 demonstrates the correlation between the significant increase in the number of summer rains from the 1990s and the increase in the annual probability of triggering debris flows during that time period.

An intensification of storms is especially a concern for the Mediterranean region where its unique topography can amplify flood waves; the catchments are often characterised by steep slopes and urban developments downstream and along the shoreline. Since the catchments are generally not very large in area, the reaction time for a flood is usually below one hour and doesn't exceed 12 hours. This provides a challenge for hydrologists who must set up models with sufficient resolution that can produce meaningful forecasts within a few minutes, even for extreme events.

Overall, the future of the Var and Vesubie catchments is uncertain. Therefore, hydrologic models need to account for a variety of different scenarios and their associated uncertainties. The unpredictable impacts of climate change on the models are discussed. Firstly, the complexity of climate processes and natural climate variability complicate future climate projections. This uncertainty can make it difficult to incorporate long-term changes into flash flood models, especially when making long-term planning and adaptation decisions. With climate change, the variability of precipitation may increase, meaning that extreme precipitation events become more frequent and intense. This increased variability makes flash flood forecasting more challenging as models need to accurately capture these extreme weather events. Additionally, climate change can lead to modifications in precipitation patterns in the Vésubie region. For example, there may be seasonal shifts in rainfall periods, changes in the spatial distribution of precipitation, or alterations in the frequency of extreme rainfall events. These modifications may render historical data used for calibrating hydraulic and hydrological models obsolete.

Anthropological factors and a changing climate can cause changes in the local landscape, such as deforestation, increased urbanisation, soil erosion, or alterations in watercourses and flow regimes. These changes can affect the topography and hydrology of the region, which in turn influences how flash floods occur and propagate in the landscape. To account for the effects of climate change on flash floods, it may be necessary to develop more sophisticated and complex hydraulic and hydrological models. This may include integrating new data and climate variables, as well as using advanced modelling techniques to simulate interactions between climate, hydrology, topography, and other factors. In summary, climate change presents significant challenges for modelling flash floods in the Vésubie region, particularly regarding data reliability, projection accuracy, and the need for infrastructure and risk management practices adaptation.

Choice of the Climate Model

The Copernicus Interactive Climate Atlas uses 4 models to simulate future climates: CNRM-CM6-1, CNRM-CM6-1-HR, CNRM-ESM2-1 and IPSL-CM6A-LR. The advantages and disadvantages of a range of climate models, including the selected CNRM-CM6-1-HR are listed in Table 1.

Table 1: Advantages and disadvantages of the four different climate models.

Model	Advantages	Disadvantages
CNRM-ESM2-1	Effective for modeling **terrestrial and oceanic processes.** Assessment of **long-term impacts** (biosphere-atmosphere interaction).	Less precise locally (CNRM-CM6-1-HR). **Less accurate for extreme events.** Underestimation of output parameters
IPSL-CM6A-LR	Effective for modeling **climatic processes.** Good performance for **overall precipitation and temperatures**. Suitable for **varied scenarios.**	Less precise locally (CNRM-CM6-1-HR). **Less accurate for clouds and extreme precipitation.** Overestimation of output parameters.
CNRM-CM6-1-HR	Effective for modeling **precipitation and extreme events**. High spatial resolution: **locally accurate**.	High computational cost. Underestimation of output parameters.
CNRM-CM6-1	Suitable for modeling a **wide range of climate variables.** **Good general balance** between performance and computational cost.	**Less precise locally** (CNRM-CM6-1-HR). May require downscaling for accurate local-scale analysis. Underestimation of output parameters.

- CNRM-CM6-1 is a climate model developed for the Coupled Model Intercomparison Project Phase 6 (CMIP6). The model integrates land surface systems, lakes, oceans and the earth's atmosphere to provide high-performance output for parallel simulations. The phase 6 version has a larger climate sensitivity than its predecessor CMIP5 (Voldoire et al., 2019).
- CNRM-CM6-1-HR was selected as the chosen climate model as it is a higher-resolution version of CNRM-CM6-1 and it is effective for modelling precipitation and extreme events, which are the major topics of our research (Voldoire et al., 2019).
- CNRM-ESM2-1 is an Earth system model offering a high model complexity as it incorporates the carbon cycle, aerosols and atmospheric chemistry. This model has been found to dampen future warming scenarios by 10% when compared to CNRM-CM6-1 (Séférian et al., 2019).
- IPSL-CM6A-LR studies the climatic responses to natural and anthropogenic activities. The model assesses climatology using a range of variables including radiation, temperature, precipitation and wind. While this version of the model is improved compared to previous versions, there are still known biases and shortcomings including the dynamics of El Niño (Boucher et al., 2020).

Presentation of the scenarios

The Shared Socioeconomic Pathways (SSP) scenarios are projections used to explore different trajectories of socio-economic development and greenhouse gas (GHG) emissions in the context of studying the impacts of climate change. Each SSP scenario represents a unique combination of demographic, economic, technological, political, and social factors that shape how societies could evolve in the future (Riahi et al., 2017). With 5 SSPs, SSP1 assumes mass sustainability efforts and environmental conservation and SSP5 is representative of a fossil fuel-dependent society with limited sustainability efforts (*Figure 6).*

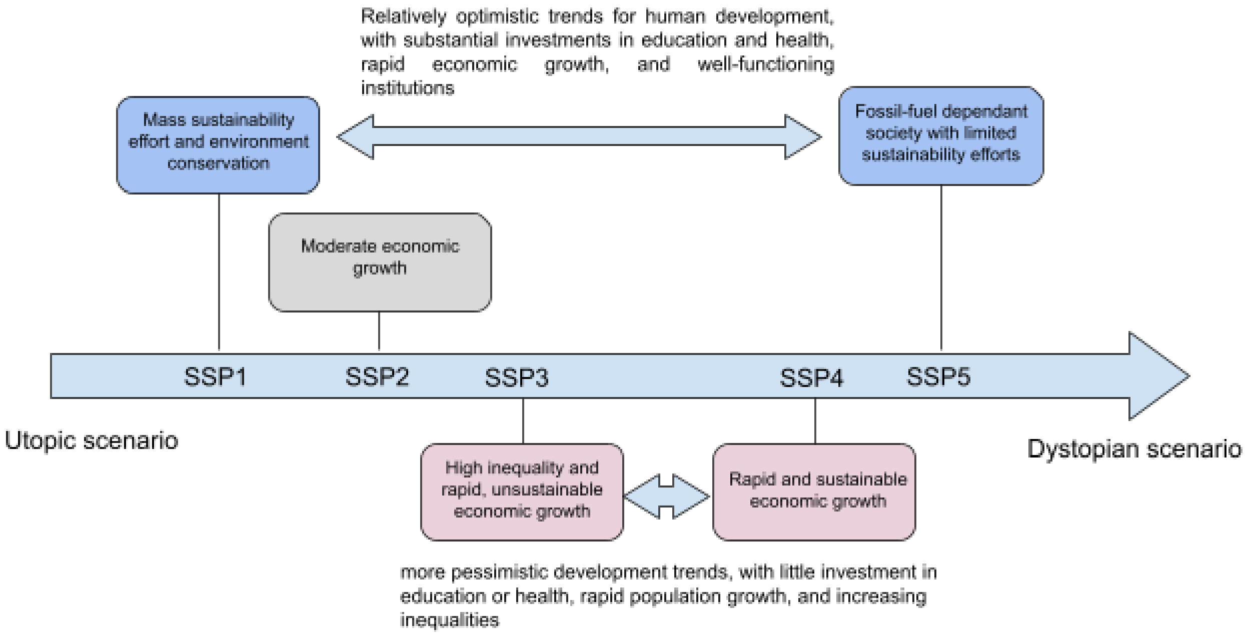


Figure 6: Explanation of the different Shared Socioeconomic Pathways

Below is a detailed description of the various aspects considered in the SSP scenarios:

- **Demographic Factors**: The SSP scenarios take into account demographic projections for different regions of the world, including population size and composition, population growth rate, urban and rural distribution, international migration, and buildings lifespan.
- **Economic Factors**: These include variables such as GDP per capita, economic growth, income distribution, economic structure (dominant industries), consumption and investment levels, as well as economic policies such as trade liberalisation or financial market regulation.
- **Technological Factors:** The SSP scenarios consider technological advances in different sectors such as energy, agriculture, transportation, information and communication technologies, as well as their global diffusion.
- **Political Factors**: These encompass national and international policies related to governance, regulation, climate agreements, carbon taxes, subsidies, energy policies, adaptation and mitigation policies for climate change, as well as international conflicts and cooperation.
- **Social Factors**: They include aspects such as education, health, gender equality, culture, social values, lifestyles, consumption behaviours, access to resources, food security, social cohesion, and risk perceptions.

Each SSP scenario combines these different factors to create plausible and coherent futures based on different trajectories of socio-economic and technological development. These scenarios are used by researchers to explore a range of possible outcomes regarding GHG emissions, climate change impacts, vulnerabilities, and adaptation options in various areas such as agriculture, water, energy, ecosystems, health, and the economy. They help inform policymakers about policy choices and strategies to address the challenges of climate change and guide societies toward a more sustainable and resilient future.

In summary, the SSP scenarios offer a range of alternatives for assessing the potential impacts of climate change on flash floods in the Vésubie region, ranging from a trajectory of sustainable development with moderate impacts to a high-development trajectory with potentially devastating consequences. Identifying and implementing effective adaptation measures will be essential to mitigate risks and strengthen the region's resilience to these growing climate challenges.

In the context of studying flash floods in the Vésubie region, where climate change can have a significant impact on precipitation, runoff, and flood risks, three SSP scenarios have been selected. Assessment of several of these scenarios allows us to identify the potential impacts associated with different trajectories of GHG emissions and socioeconomic development and therefore make informed decisions to address climate change.

To assess the potential impacts of climate change, 4 Representative Concentration Pathways (RCP) are often utilised. RCP are projected greenhouse gas (GHG) concentrations based on socioeconomic, technological, and policy developments. RCP2.6 is the lowest emission scenario, assuming a mid-century peak in global GHG emissions and then a decline in emissions. In this pathway, global warming remains below 2 °C due to intense mitigation efforts. Contrastingly, RCP8.5 is the highest emission scenario and assumes business-as-usual leading to a significant increase in global temperatures. Combining an RCP and SSP builds a scenario which integrates climate change and socioeconomic factors. Assessment of several of these scenarios allows policymakers to research the potential impacts associated with different trajectories of GHG emissions and socioeconomic development and therefore make informed decisions to address climate change

Scenario 1: SSP1-2.6 (Sustainable Development)

The SSP1 (Shared Socioeconomic Pathway 1) is one of the five scenarios of socio-economic development used in climate change research. This scenario combines SSP1 and RCP2.6. SSP1 describes a trajectory of socio-economic development where the global population peaks relatively early and begins to decline, fertility rates decrease, and the population ages. Technological progress is rapid, leading to increased resource efficiency, growing use of renewable energies and clean technologies, and improved waste management (Riahi et al., 2017). In this scenario, policies and institutions favour sustainable development, reducing inequalities, and environmental protection. There is strong international cooperation, with agreements and concerted actions to combat climate change, protect biodiversity, and promote equitable development.

The SSP1-2.6 scenario represents a trajectory where GHG emissions are greatly reduced through the rapid adoption of policies and technologies aimed at mitigating climate change with net zero emissions reached after 2050. In this context, the Vésubie region could experience moderate increases in extreme precipitation and flood risks, but these impacts could be mitigated by effective adaptation measures (GIEC Report, 2021). For example, the SSP1-2.6 scenario corresponds to a sustainable development that would limit the temperature rise to 1.8°C by the end of the century (Gouv, 2022). Investments in stormwater management infrastructure, restoration of natural ecosystems such as wetlands, and sustainable land management policies could help reduce flash flood risks. Additionally, more sustainable agricultural and urban practices could help minimise the impact of intense precipitation on soils and watersheds, thereby reducing runoff and flood risks (Riahi et al., 2017).

In summary, SSP1 represents an optimistic vision of the future, characterised by sustained economic growth, stabilised population, significant technological advancements, and effective global cooperation to achieve sustainable development goals.

Scenario 2: SSP2-4.5 (Intermediate Development)

The SSP2 (Shared Socioeconomic Pathway 2) is one of the Shared Socioeconomic Pathways used in climate change research to describe different future trajectories of global development. This scenario combines SSP2 with RCP4.5. SSP2 represents a middle-of-the-road scenario characterised by:

- **Medium population growth**: SSP2 assumes that global population growth will continue but at a moderate pace, with population reaching around 9 to 10 billion by the end of the century.
- **Balanced development**: This scenario assumes a mix of economic development and inequality reduction, with moderate improvements in living standards for most of the world's population.
- **Medium technological progress**: SSP2 envisions a future where technological progress continues at a moderate pace, with improvements in energy efficiency and some adoption of low-carbon technologies, but without any major breakthroughs.
- **Medium environmental policies**: This pathway assumes that environmental policies will be implemented, but with mixed success, resulting in moderate levels of environmental degradation and resource depletion (Lepousez & Aboukrat, 2022).

The SSP2-4.5 scenario represents a trajectory where GHG emissions remain similar to the current scenario before declining in the mid-century. Net zero is not yet reached by 2100 in this case. For example, regarding the sea level by 2100, the average sea level would rise compared to the 1995-2014 average by 0.28 to 0.55 meters under this scenario (GIEC Report, 2021). In this context, the Vésubie region could still face significant increases in extreme precipitation and flood risks. Adaptation measures would need to be more substantial than in the SSP1-2.6 scenario to address these growing challenges. This could include additional investments in flood protection infrastructure such as levees and dams, as well as land management measures to reduce runoff and soil erosion. Urban planning and territorial development strategies may also be necessary to reduce the exposure of populations and assets to flood risks.

Overall, SSP2 represents a future where economic and social conditions evolve at a moderate pace, without extreme changes in population, economy, or technology. It is often used as a reference scenario for assessing climate impacts and policy responses that fall between more optimistic and more pessimistic pathways (GIEC Report, 2021).

Scenario 3: SSP5-8.5 (High Development)

SSP5 represents a trajectory where economic growth is prioritised at the expense of environmental sustainability with RCP8.5. Below is a detailed explanation of SSP5:

- **Strong Economic Growth:** SSP5 assumes continued and robust economic growth globally. This growth often relies on intensive use of natural resources and rapid expansion of industrial and commercial sectors.
- **Advanced Technology**: This scenario also assumes rapid and widespread technological development. Technological advancements are used to enhance economic efficiency, but they can also lead to intensified exploitation of natural resources.
- **Low Environmental Concern**: Unlike other SSPs that prioritise environmental sustainability, SSP5 assumes that environmental considerations are sidelined. Economic policies and decisions are primarily focused on maximising economic growth and prosperity.
- **Persistent Inequalities**: In this scenario, economic and social inequalities persist or even worsen. Economic growth primarily benefits elites and dominant industries, while large segments of the population may remain in poverty or see stagnant living conditions.
- **Pressure on Natural Resources**: Due to rapid economic growth and intensive resource use, SSP5 generates significant pressure on natural resources, including water, land, and fossil fuels. This pressure can lead to environmental issues such as deforestation, pollution, and biodiversity loss (Lepousez & Aboukrat, 2022).

The SSP5-8.5 scenario represents a trajectory where GHG emissions continue to increase significantly in the absence of significant efforts to reduce them. In fact, CO_2 emissions are simulated to double current emission rates by 2050. In this context, the Vésubie region could face increasingly frequent and intense flash flood events, with potentially devastating consequences for local communities, infrastructure, and the regional economy. Adaptation measures in this scenario could be particularly complex and costly, requiring massive investments in flood protection infrastructure, as well as efforts to reduce GHG emissions on a global scale. Fundamental changes in economic and social development policies would also be necessary to mitigate the impacts of climate change on the Vésubie region and ensure its resilience to flash floods in the future. For example, this scenario would lead to a temperature rise of 4.4 °C and a sea level increase between 0.63 and 1.02 m by 2100. This is an increase of 41 % of the temperature compared to scenario 2.6.

In summary, SSP5 describes a future where economic growth is prioritised over environmental sustainability, with persistent inequalities and intensive use of natural resources. This scenario highlights the challenges and risks associated with a development approach that disregards environmental and social limits.

Data Collection

From the Copernicus Interactive Climate Atlas, the change in the maximum of 1-day precipitation data (in mm) for each of the 3 scenarios (SSP 1-2.6, 2-4.5 & 5-8.5) was downloaded for the Mediterranean region using the CNRM-CM6-1-HR model. A long-term projection was used which is for the years 2081 to 2100. The maximum 1-day precipitation for this period was compared with the 1991 to 2010 period and from this, a percentage change was calculated. The results for the three climate scenarios are seen in Table 1 below. The most optimistic scenario (SSP1-2.6) relates to an 11.5% increase in the 1-day precipitation maximum while the most pessimistic scenario (SSP5-8.5) corresponds to almost double the increase at 22.7%.

Table 2: Three scenarios and their respective percentage change in the 1-day maximum precipitation

Scenario	Increase in 1-day precipitation maximum
Scenario 1: SSP1-2.6 (Sustainable Development)	11.52%
Scenario 2: SSP2-4.5 (Intermediate Development)	14.80%
Scenario 3: SSP5-8.5 (High Development)	22.73%

To compare the different climate scenarios, the percentage increase was used to simulate precipitation data for a storm with a 100-year return period. To compare with the current state of the catchment, data from Storm Alex with a 500-year return period was used to create a Gumbel curve from which a new data set for a 100-year return period storm was created. Therefore, a 100-year flood is simulated in the hydrologic and hydraulic models under current conditions and under the 3 climate change scenarios. First, the precipitation data is input into the hydrologic model (HEC-HMS) to provide us with the discharge data. Next, the discharge data is run in the 1D MIKE-11 model and the 2D TELEMAC model to assess the flooding impacts under the different climate scenarios. By integrating the climate scenarios into our model, we can assess the potential future impacts of climate change on flash floods in the region. This approach allows us to better understand the range of challenges the Vésubie region might face, enabling us to develop more informed and adaptive strategies for flood risk management in the future.

Hydrologic Model: HEC-HMS

In our project on flash flood modelling of the Vésubie, we have successfully developed a hydrological model that functions effectively for a 100-year return period. The HEC-HMS model has been calibrated using Storm Aline and validated using the Alex Storm. A sensitivity analysis was also performed using the curve number which can be found in Report 1. In this phase, HEC-HMS was used to input the precipitation data of the three potential future 100-year return period rainfall events. The resulting discharge data was run in the MIKE-11 and TELEMAC models.

Hydraulic Model: TELEMAC-2D

Objective

The objective of the TELEMAC-2D model was to simulate the precipitation events under different climate scenarios in order to predict the effects of flash floods in the future. Then, we can select an area for the construction of the wastewater treatment plant which is not as affected by flooding. For this, the maximum head will be simulated under the following scenarios:

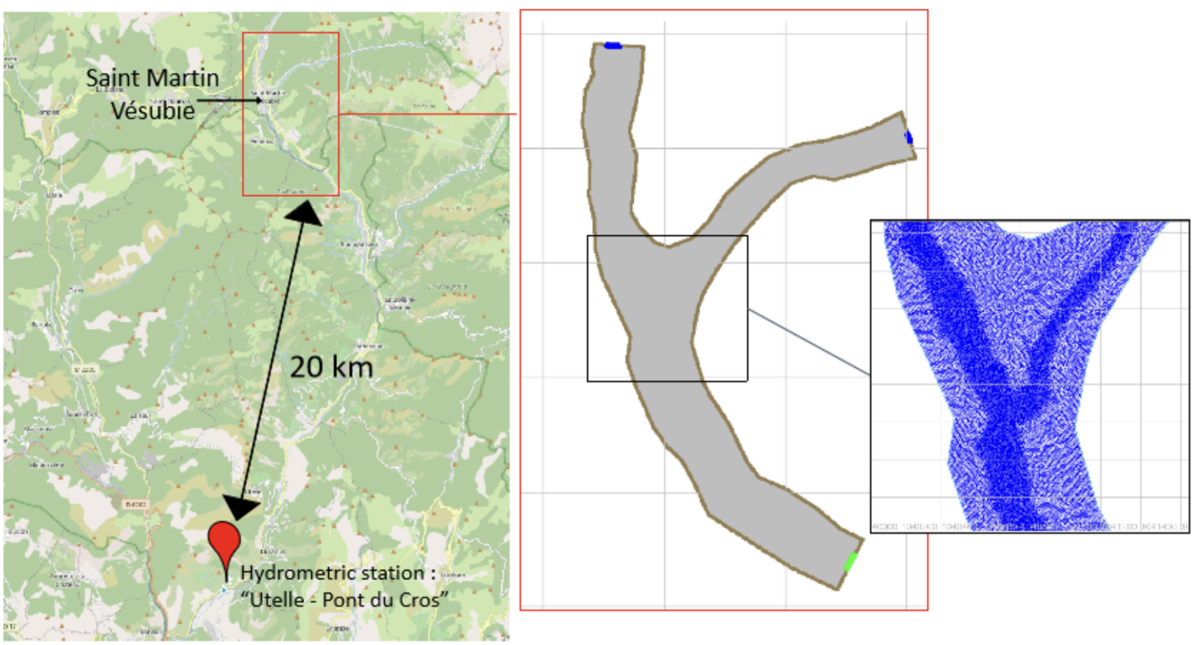
- Scenario T: Flood Hydrograph T=100 (Current Conditions)
- Scenario 1: SSP1-2.6 (Sustainable Development)
- Scenario 2: SSP2-4.5 (Intermediate Development)
- Scenario 3: SSP5-8.5 (High Development)

First, the parameters needed to build the TELEMAC model are discussed here. This includes the model mesh, bathymetry, selection of the boundary conditions and the Manning coefficient.

Model Construction

Model mesh

After importing the contours into BlueKenue, we selected the T3 Mesh Generator tool with a 5 meters mesh size for the minor bed. For the major bed, less critical, we opted for a mesh size of 10 meters. The result of the mesh is shown in Figure 7.



Localisation of the station *Visualisation of the mesh and the boundaries conditions*

Figure 7: Location of the hydrometric station, mesh size and boundary conditions in TELEMAC

Bathymetry

After generating the mesh, we used the 2D Interpolator tool to interpolate bathymetric data extracted from the Digital Field Model (DTM) into the previously created mesh. Subsequently, during this interpolation step, the Selafin Object tool was used to create the required .slf geometry file for TELEMAC. The results are seen in the following figure.

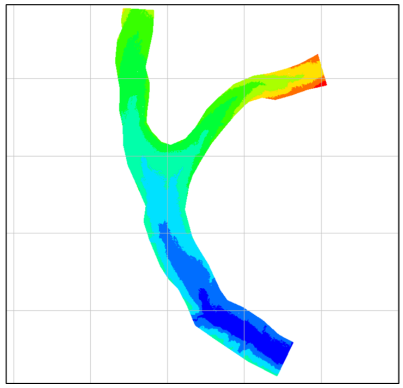


Figure 8: Bathmetry *in TELEMAC*

Boundary conditions

The last step is to generate the boundary conditions file. Using the boundary conditions tool, we create the .cli file required for TELEMAC, where we introduce the flow rate of the selected upstream scenarios on the boreon and the madone, as well as a zero water height downstream. The locations of the boundary conditions are seen in Figure 7.

Manning coefficient

The Manning coefficient of each section was selected based on its land use. For this, the study area was categorised into 9 different land use types, as seen in the figure below. This map will also be utilised to assess the optimum location for the new WWTP.

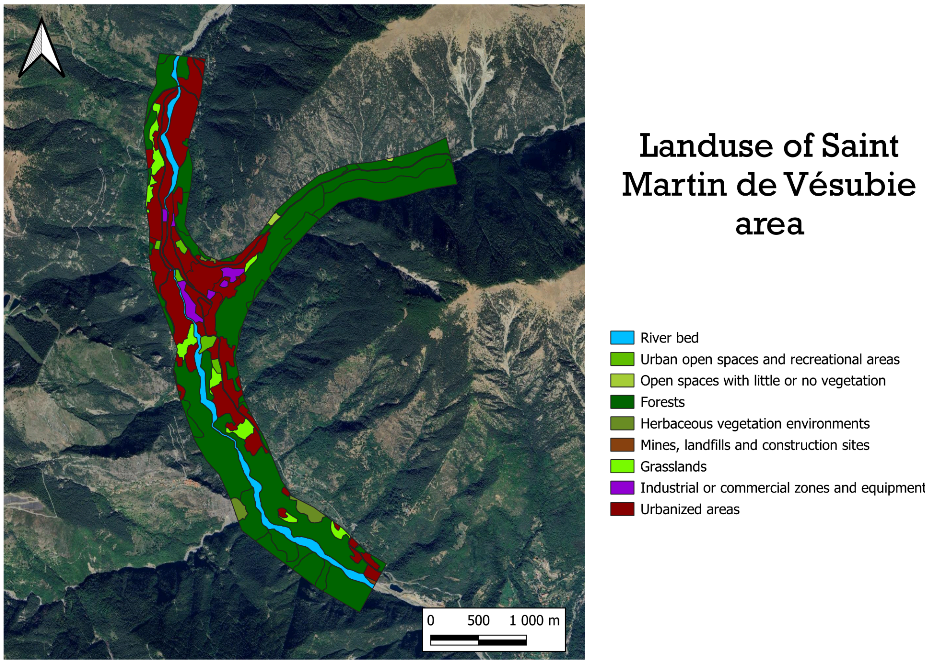


Figure 9: Land use for the study area

Results

Firstly, the TELEMAC results for the current scenario are assessed. As mentioned, a 100-year return period precipitation event is run in the model.

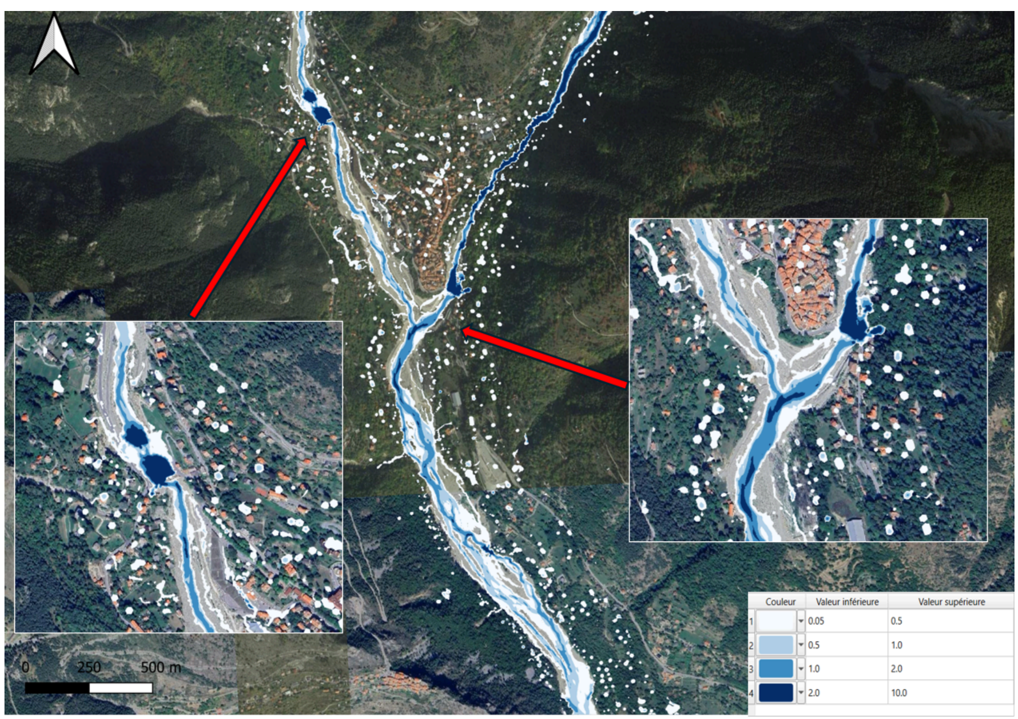


Figure 9: H_{max} with current scenario T = 100

As can be seen in Figure 9, the head is highest northwest and southwest of the Saint-Martin-de-Vésubie area. Under the current situation, most of the city experiences a maximum head of 0.5 m during a 100-year precipitation event.

For the first climate change scenario representing sustainable development (SSP1-2.6), the 100 year precipitation event was increased by 11.52% and the results are seen in Figure 10. Compared with the current scenario, the head greatly increases south of the urban area where the two streams meet. We see more areas under a maximum head of 2 to 10 m, which can cause considerable damage to the area surrounding the confluence, especially in the southeast part of Saint-Martin-de-Vésubie.

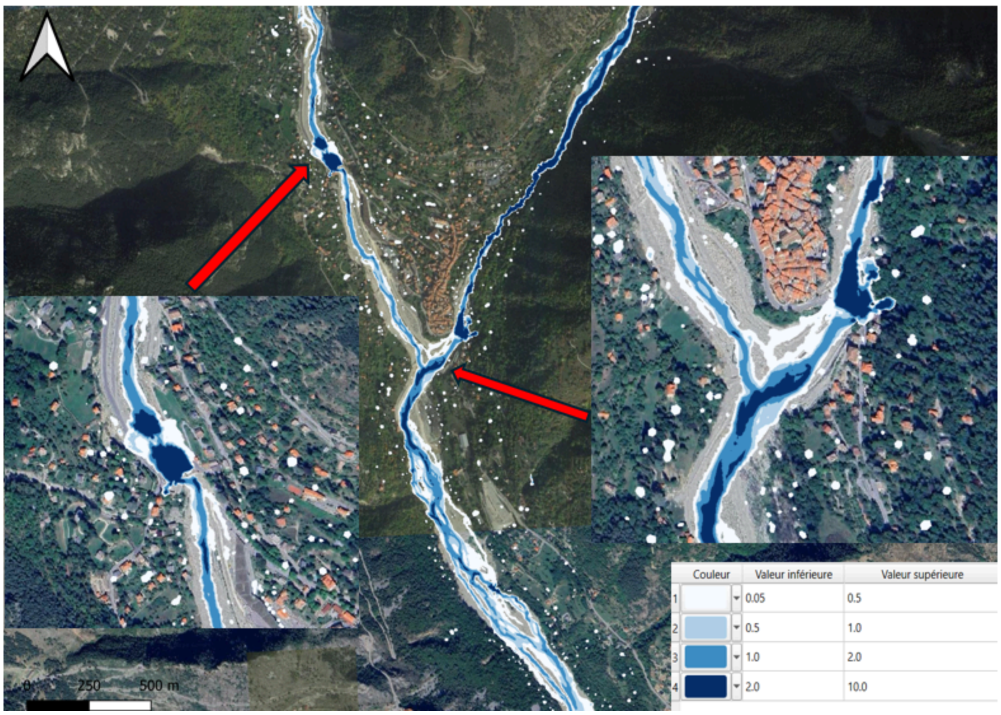


Figure 10: H_{max} with Scenario 1: SSP1-2.6

For the 2nd scenario representing intermediate development (SSP2-4.5), the results are comparable to the sustainable development scenario. In the river, many areas experience a maximum head of 2 to 10 m while the areas more than 50 m away from the river still experience a maximum head of only 0.05 to 0.5 m.

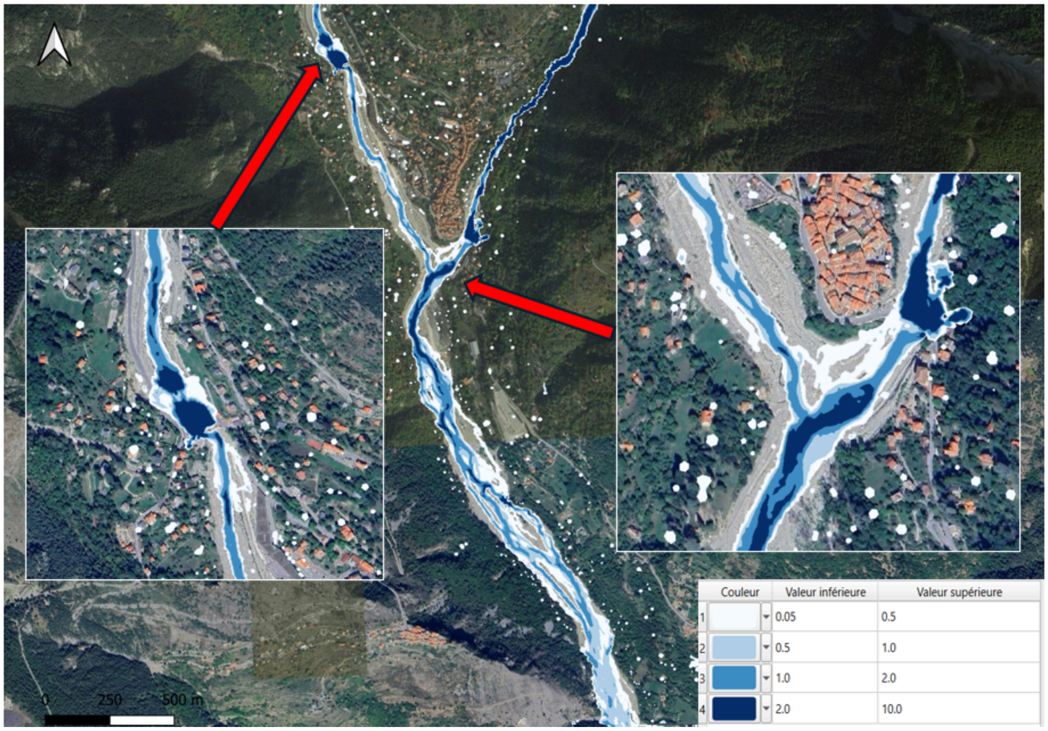


Figure 11: H_{max} with Scenario 2: SSP2-4.5

Finally, the high development scenario (SSP5-8.5) is presented in Figure 12. There is a larger area in the northwest of Saint-Martin-de-Vésubie that experiences a maximum head of between 2 to 10 m. This is of high concern for the buildings located next to the river, of which there are quite a few as seen in Figure 12. Additionally, the entire eastern stream and the Vésubie river after the stream confluence experiences a head of between 2 to 10 m. Most at risk in Saint-Martin-de-Vésubie is the southeastern part of the city which is built very close to the river and is just north of the confluence.

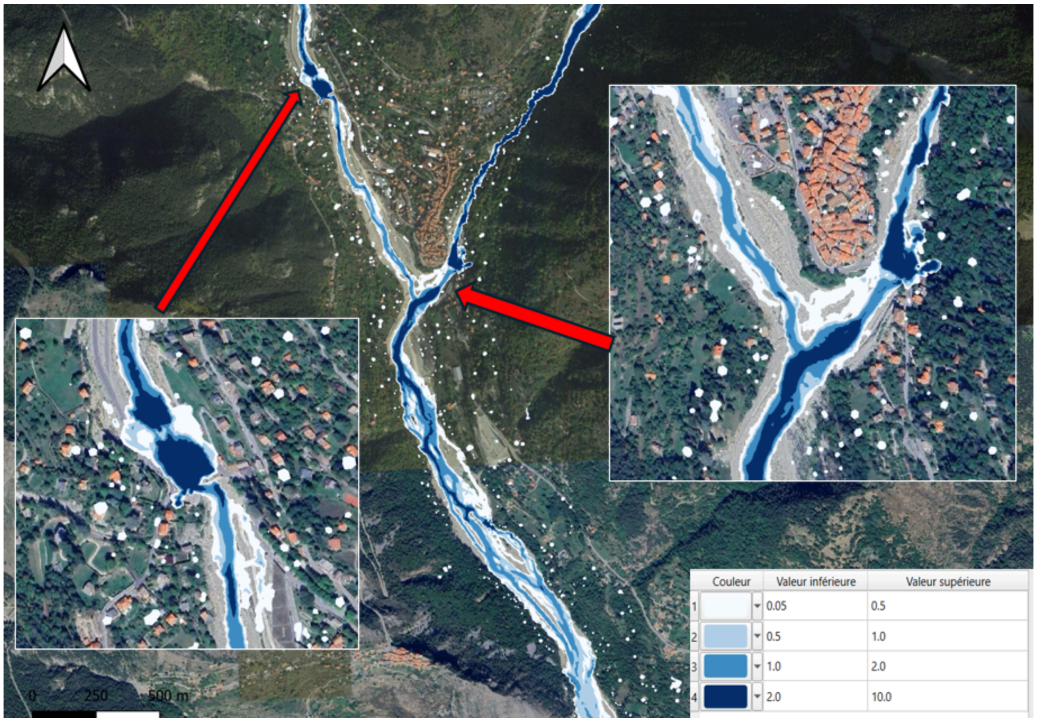


Figure 12: H_{max} with Scenario 3: SSP2-4.5

To visualise the differences in the climate change scenario, the maximum water depth variation is rperesented in Figure 13. The graph represents the water depth over the course of the 100-year return period precipitation event at the confluence of the two streams (Madone and Boréon), as this is the area which experiences some of the highest head during precipitation events. As expected, the 3rd climate scenario (SSP5-8.5) causes the highest head which reaches almost 2.8 m at its peak. The other two future scenarios are very similar and experience a maximum head around 2.6 m. 4 hours after the peak, the two more optimistic scenarios lead to a head around 1.9 m at the streams confluence while the pessimistic scenario causes a head of 2 m at the same location. To ensure minimal future detrimental impacts of flooding events in the Vésubie subcatchment, adequate measures should be taken to minimise the impact of climate change.

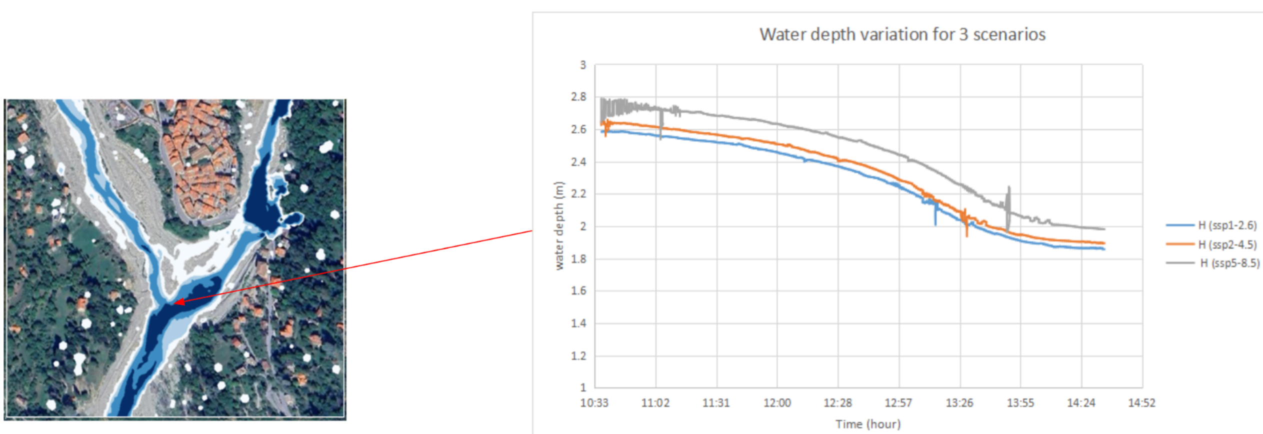


Figure 13: Water depth variation for the 3 climate change scenarios

Hydraulic Model: MIKE-11

To verify the TELEMAC model results and the selected location of the new WWTP, a different approach was taken for modelling the water level in MIKE-11. From Copernicus, the projected daily precipitation values for the years 2015 to 2100 were downloaded based on the CNRM-CM6-1-HR model and the sustainable development scenario (SSP1-2.6). The 85 years of predicted precipitation data was run in HEC-HMS to generate discharge values.Then, an extreme value analysis was conducted using WETSPRO (Willems, 2009). By establishing a relationship curve between return period and peak discharge, the peak flow corresponding to a 100-year return period was approximately 78 m^3/s. Subsequently, a normal distribution probability density function was employed to construct a 24-hour hydrograph input for MIKE11. The results are seen in the following figure.

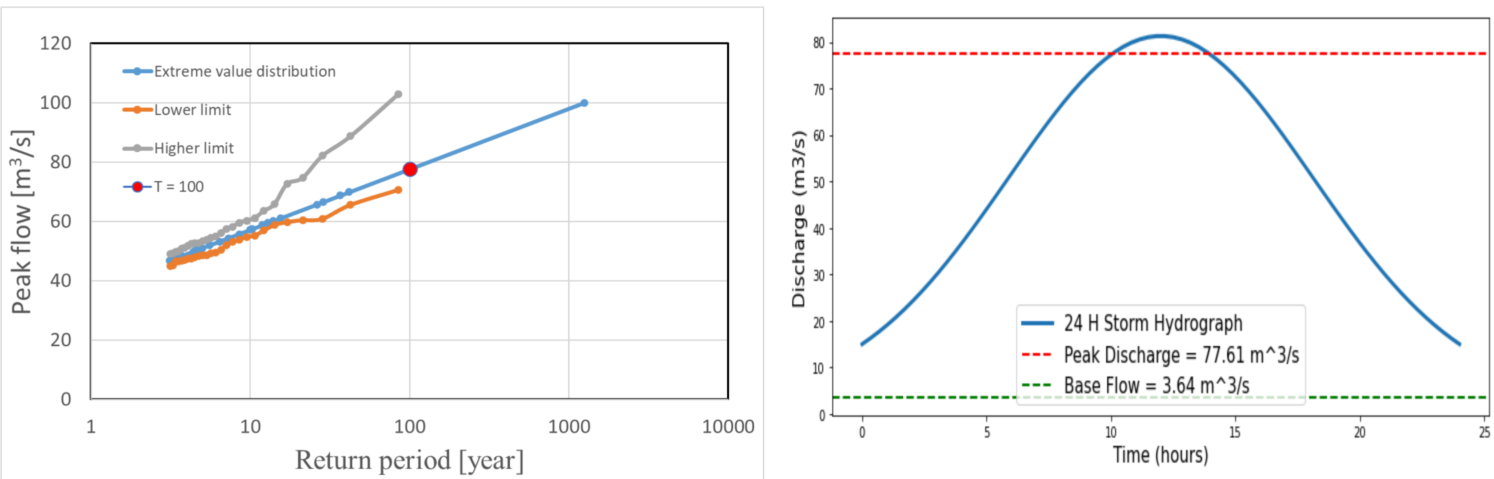


Figure 14: (A) Extreme value distribution (B) storm hydrograph for the 100-year precipitation event

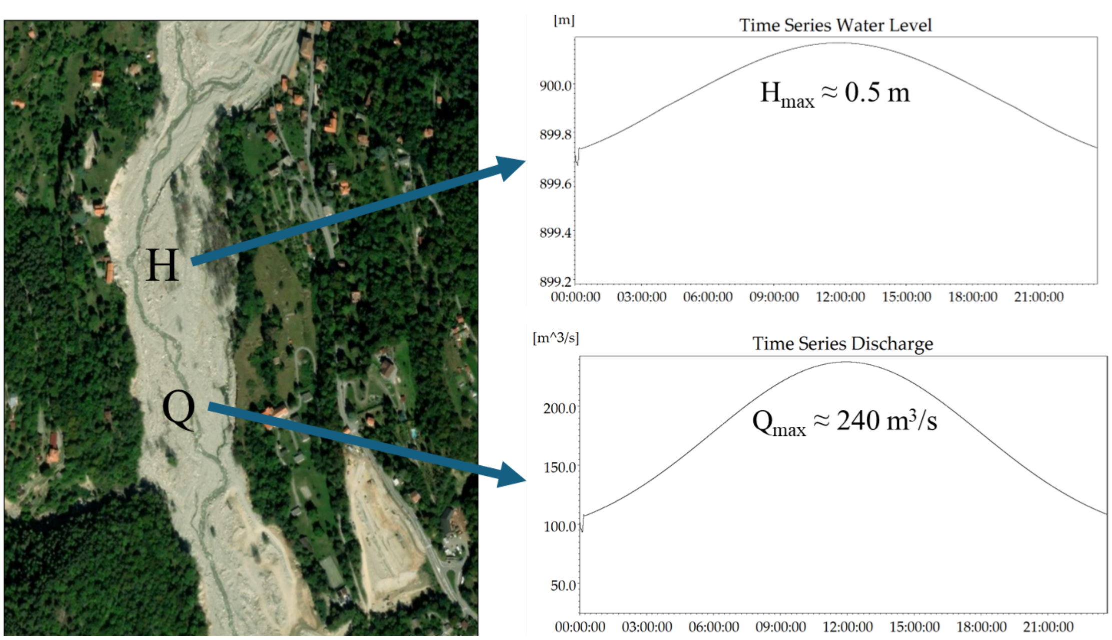


Figure 15: Maximum head and discharge for a 100 year storm event under SSP1-2.6

In this context, the area east of the Vésubie river, which we have chosen as the location for the new WWTP, has a maximum discharge of 240 m^3/s and a maximum water level of up to 0.5 m. These results are for a storm event with a return period of 100 years and lasting for 24 hours. This level of impact is similar to that experienced during the Aline storm in October 2020.

However, it's important to note that uncertainties exist in the calculation of peak flow during extreme value analysis. We computed ranges of variation within a 95% confidence interval and inputted them into the MIKE-11 model to determine the variability in maximum water level and discharge. Under this scenario, the maximum water level and discharge can reach up to 0.65m and 309.8 m^3/s, respectively. To compare with the current scenario, data from a nearby gauging station was used, seen in Figure 16. Since 2021, the maximum head experienced in this area is 0.5 m. Therefore, if the goals of SSP1-2.6 can be achieved, the overall flood pressure faced in the future would be manageable.

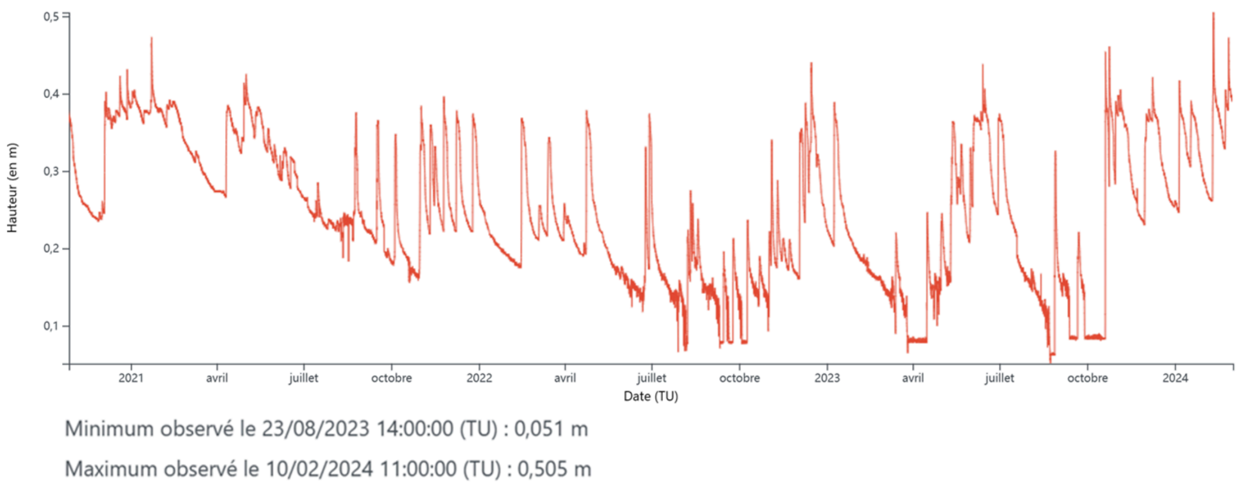


Figure 16: Water level experienced near the chosen location of the WWTP since 2021

Conclusion

This report has explained the use of a hydrologic model and two hydraulic models which were calibrated using data from previous flash flooding events in order to predict future inundation behaviour under different climate scenarios. Using three different possible future scenarios, the potential impacts of climate change on flash floods in the Vésubie region are assessed and a recommendation can be made for a new wastewater treatment plant in Saint-Martin-de-Vésubie. The site must be at a low flood risk for the current climate and potential future climates.

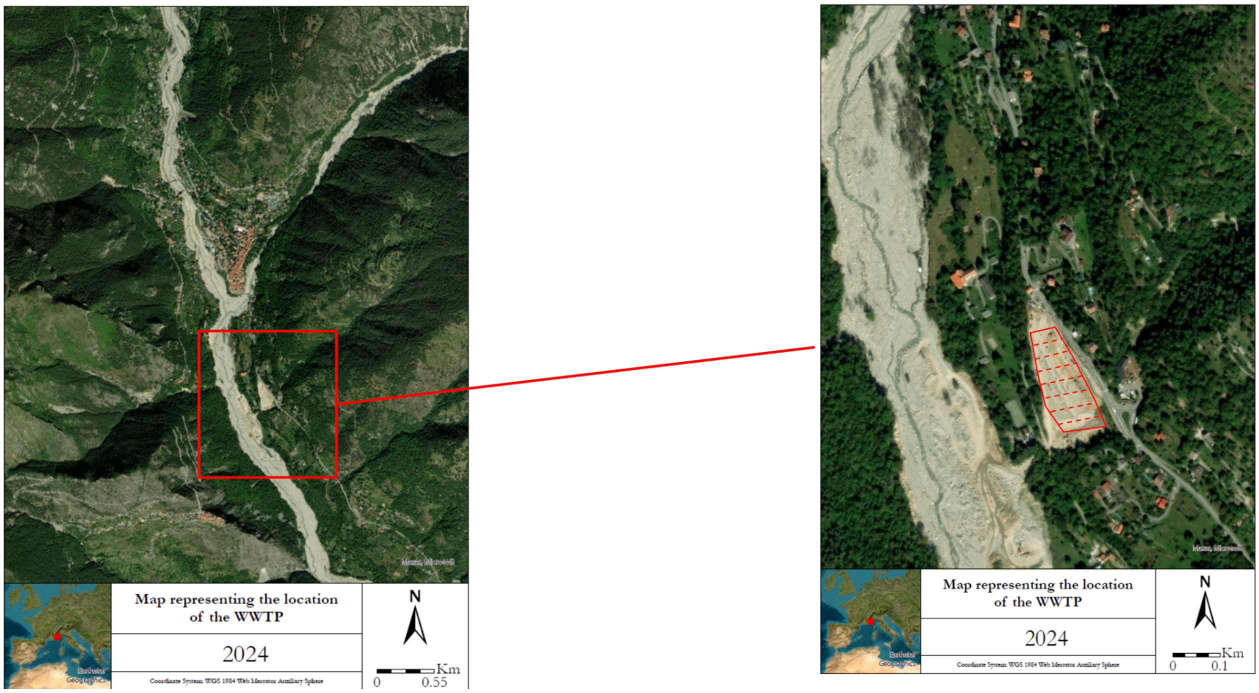


Figure 17: Location of the new wastewater treatment plant in Saint-Martin-Vésubie

The final location of the WWTP is chosen to be to the east of the Vésubie River just south of the confluence of the two streams. This location was chosen because it is downstream of the urban area. There was also a suitable location north of the urban area, however, it is not feasible to build the WWTP upstream where pumping is required to transport the wastewater to the plant. Instead, the southern location is ideal because the wastewater can be gravity-fed. Additionally, the area north of the population is classified as private land and therefore will cause delays in the acquisition of this land and construction agreements. In previous floods, the area west of the river has been severely damaged and therefore is not an optimum location for the WWTP. This area experiences a maximum head of only 0.5 m during a 100-year precipitation event, even in the high development worst case future scenario, as modeled by TELEMAC. The results from MIKE-11 confirm that this area experiences minimal impact during a 100-year precipitation event. The land in the chosen area is slightly urbanised with forest surrounding. It is about 10 m in elevation above the river. For these reasons, the highlighted area in Figure 17 is chosen for the new Saint-Martin-Vésubie WWTP.

Team Members

Team Member	Role	Tasks Completed
Romain	Team Manager	• Manage the team • Website editing • Report writing (climate change scenarios)
Paulien	Report Manager	• Report writing • Report formatting • Field trip report write-up • Climate change research
Delphine	Data processing, TELEMAC, uncertainty & sensitivity analysis	• Presentation formatting • Report writing • Climate change and model research
Ziad	Data processing	• Climate change data processing • Return period data • Background information
Abir	Data processing	• Climate change data processing
Sam	HEC-HMS	• Running model with climate change effects • Climate change and model research
Manon	HEC-HMS	• Assisting with HEC-HMS model
Huangling	MIKE-11	• Running model with climate change effects • Field trip report • Data processing
Eunyoung	MIKE-11	• Climate change impact research
Sitraka	TELEMAC	• Running model with climate change effects • Climate change data processing
Fidele	TELEMAC, uncertainty & sensitivity analysis	• Assisting with TELEMAC model • TELEMAC result processing • Report writing

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Field Trip Report

On February 24th, the team took a field trip to the Var catchment. The first stop was at the CAP3000 commercial area and the airport. This place is the outlet of the Var catchment. 90% of the time the flow rate here is about 35-40 m3/s. The minimum can reach 10 m3/s. During the Alex storm event, on October 2, 2020, the highest recorded discharge and water level reached 2560 m3/s and 4.97 m, respectively (Hydroportail). The Var is the largest river between Italy and Marseilles as the other catchments are usually small. The airport is located on reclaimed land which means it is especially vulnerable to flooding and was even closed for over a week after the 1994 flood. There are pipes located at this part of the river to drain water during extreme precipitation events, however, during the most recent flood, a miscommunication led to the valves remaining closed and the entire commercial centre was flooded.

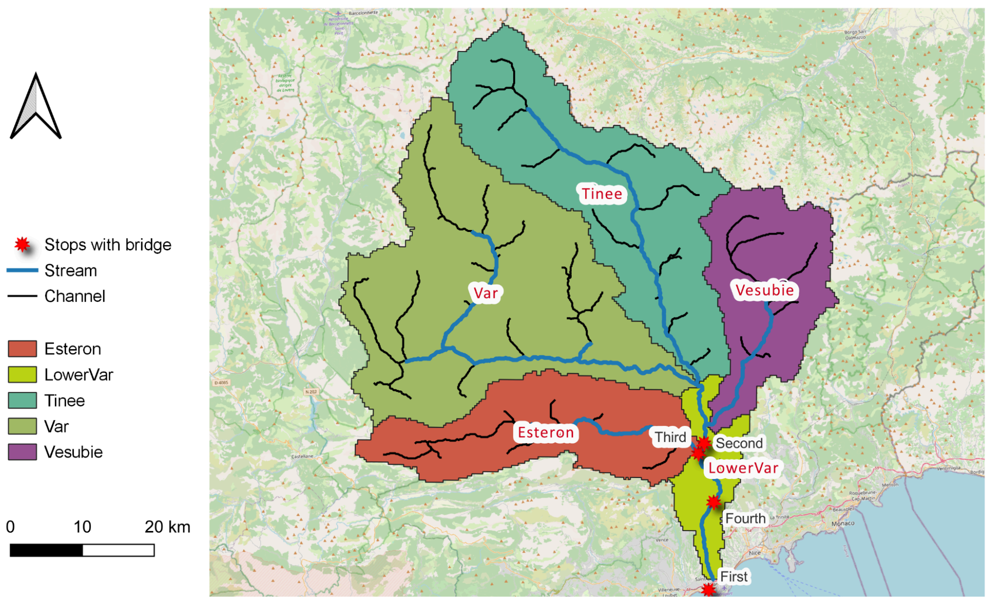

Figure 1: The location of the stops during the field trip of the Var catchment.

The location of the stops taken during the field trip can be seen in the figure above. It should be noted that the first and third stops were also near discharge gauging stations.

Figure 2: The picture of four bridges during the field trip.

In 1970, ten weirs, which act like dams, were built along 25 km of the Var Valley. The objective was to control the water as the river was deeply entrenching the river bed. This was disadvantageous for farmers who were drilling the groundwater to use for crop irrigation. If the river lowers, so does the groundwater table, therefore forcing farmers to drill deeper into the ground to reach the water table. However, the weirs hold back coarse sediment and in fact, did not prevent the lowering of the river bed and the groundwater table. The impact of human activity is evident; the natural transportation of sediment is no longer possible and the government spends 2 million euros annually to transport sediment along the catchment. Additionally, the weirs increase the head and allow the stream to be used for electricity generation. Most of the time, discharge is low and therefore not much electricity is produced. During flooding, the water from the river travels mostly via the overflow and not much power is produced then either. Therefore, although the weirs are designed to produce electricity and enforce the long-term stability of the river profile, neither objectives are accomplished very well. Also, in the 1994 flood, the weir collapsed and created a large wave which caused major damage downstream. Enforcement of the weirs is essential to minimise these damages in the future, especially because there are stations which extract surface water and pump groundwater for the population of Nice.

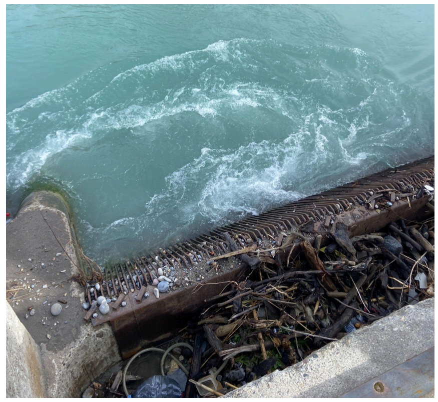

Figure 3: Weir holding back sediment and other debris in the river

We also stopped at the Charles Albert Bridge, named after the Duke of Piemont Sardaigne. Originally, it was the first bridge that crossed the Var Valley as the river was quite wild and not much technology was available yet. The original bridge that was built was destroyed 60 years ago during a flooding event. The new bridge that was built is 2 m lower than the first one. During the Alex storm event, water reached the level of the bridge. At this stop, we also discussed the levee constructed on the river. Currently, the river bed is below the protection of the levee. Additionally, the levee is not protected because it is made mostly of gravel and sand which gets eroded by the water. The levee is at risk of collapse. There are blocks of concrete, called 'sugar' to protect the levee.

The last stop was at a bridge which is extremely vulnerable due to a variety of reasons. Firstly, the bridge is an important transportation network; if the bridge gets flooded, the people are isolated from the other side until the flooding is over. Underneath the bridge are sanitation lines, therefore the destruction of the lines due to flooding could lead to pollution of the river, although this would be minor as the river is of overall great quality due to the lack of agriculture and domestic wastewater discharged in this area. More significant are the high voltage line and gas line providing services to Nice. The destruction of these lines can cause great inconveniences, social losses and economic losses during extreme flooding events to the thousands of people and businesses relying on them.