POLITECNICO DI TORINO

Department of Environment, Land and Infrastructure Engineering
(DIATI)

Climate Change Engineering (LM-35)

MASTER THESIS

Hydrological balance of the Como lake

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March 2024

INDEX

1. INTRODUCTION

Lakes are surface water bodies whose balance is defined by inflows (from rivers, precipitation, groundwater,…) and outflows (discharge and evaporation). Lakes are natural (or regulated) storages of water used by humans for several activities such as irrigation, fishing, and electrical energy production. Such uses of water are often in competition and represent the major challenge of water managers, especially in the frame of climate change.

Function of their original cavities, the lake could be based on different geological characteristics. From ecological point of view, the trophic categories exchange with the lake energy and organic materials starting from solar energy and inorganic matter.

The hydrological balance of the lake is an important step in the management of water, and it has the aim of evaluating the inflows, outflows and volume change, considering at hydrological processes. Being the lake an "open system" it is going to have a strong impact and interaction with factors as ecological, anthropical, geological, …

The aim of thesis is to define the hydrological balance of Como Lake. This is one of the most important lakes in Northern Italy and the deepest of all. The study of this lake is part of biggest project which aims at estimating the water resources and management in the Po river basin, in order to implement adaptation strategies to climate change. Specifically, the project is financed by PNRR and it is called as "*Climate adaptation for the Pò river basin district*" part of LIFE CLIMAX PO project.

The Como lake is an alpine glacial lake characterized by high water quality. Its environmental value is large and thanks to the high-water quality, it is very important for fishing, for agriculture and tourism purposes.

All hydro-meteorological data used in the study have been extracted from ARPA Lombardia and analyze before being used for the modelling. Then, additional variables have been estimated from the downloaded data, such as evapotranspiration and flow rate values. These data have been used to simulate the inflows with the hydrological HBV model, whereas the discharge has been estimated from water level data. Finally, the hydrological balance of the lake was reconstructed. The hydrological study has considered the lake variability along 18 years, which is a good time span for water management purposes.

Additionally, in the last chapter, future projections about the variability of analyzed data and adaptation measures for the lake have been proposed.

2. LAKE SYSTEM

2.1 Ecosystem of the lake

A lake could be defined as water body, typically containing fresh water, surrounded by land. This water body has typically continuous replacement of water due to inlet water (from precipitation, river, groundwater,..) and outlet water (evaporation, river,..).

Lake characteristics as extension, deepness and geological features change a lot in according with the phenomenon which generates the lake. Lakes are present in any continent and in any type of environment.

Similarly to the mountain environment, freshwaters environment is highly affected by climate change. In this type of environment lakes are present too (Rita Adrian et all., 2016).

Into the lake is present complex ecosystem characterized by plant, micro-organisms and animals and there are a lot of chemical and physical interactions within this biotic part.

A lake could be defined as the main example of lentic environment characterized by relatively stationary water (H.H. Hobbs and D.M. Lodge, 2010).

The main physical characteristics which define a lake are temperature, wind and light. These factors create a stratification into the lake which also defines the biotic environment present. The shallowest layer is called epilimnion, the deepest hypolimnion while the intermediate thermocline.

As visible in the Figure 2.1 the typical structure of lake is based on the presence of littoral zone close to the river where vegetations is present due to the penetration of light that permits at the aquatic plants to grow. From the zone in which the light penetration is lower than 1%, there is the deepest zone which is called limnetic. In this last zone the photosynthesis does not occur.

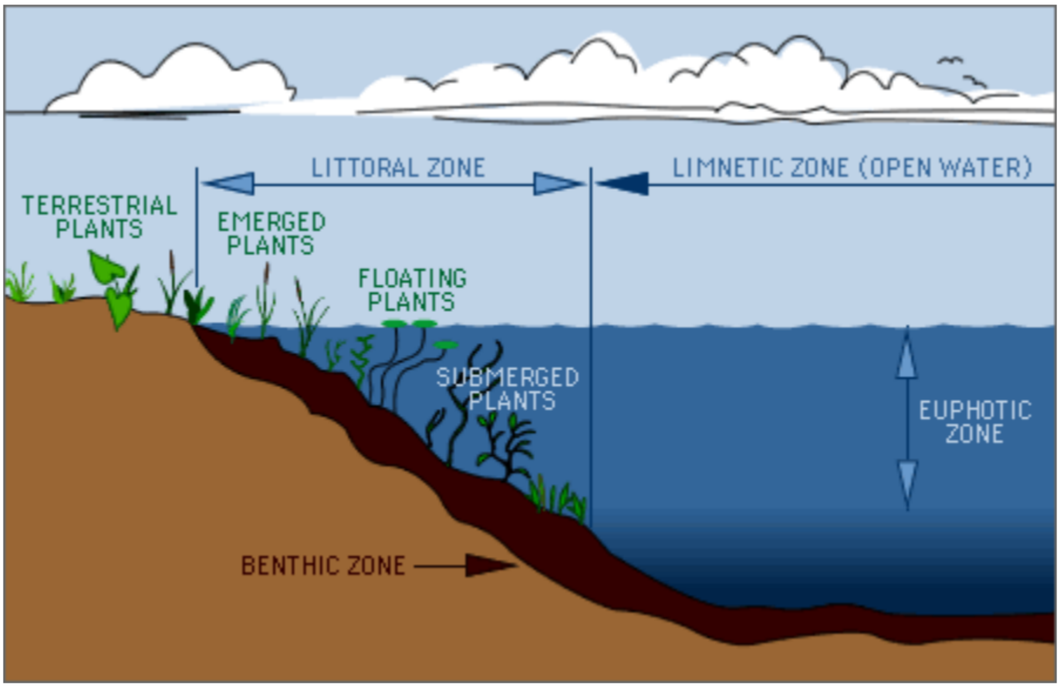


Figure 2.1 *Lake characteristic representation.*

Within the organisms which live into the lake could be described the fish, insects, and zooplankton in the superficial part. On the other hand, close to the bottom it is possible to find plankton, bacteria, and fungi, but in some cases also plants and very small and invertebrate animals.

The chemical characteristics of lake should be monitored and evaluated continuously. They are regulated by government entities and should be monitored due to the possibility of developing the phenomena of eutrophication, which is an overproduction of algae into the lake.

The lake is very important for what concern the water cycle of the Earth. But on the other hand, is also important for the human for all the uses.

2.2 Water regulations and lake characterization

The main regulation related to water management is the WFD (water framework directive) signed by any European countries.

Such type of regulation is based on the standardize the usage and the characteristics that any type of freshwater (superficial, fluvial and groundwater) should have. Additionally, it has been regulated the release of some pollutant into freshwater. The aim of that is to preserve the environmental system and improve its status through different solutions in according with the local characteristics and possibilities.

The aim to preserve the freshwater is strictly linked with the preservation of the ecosystem (aquatic and terrestrial) and humid zones. Not only limitation in term of maximum pollutant that there could be release but also regulation in term of usage and extraction of that water.

It is necessary that any Country subdivide the territory into hydrological basin and define an authority for that (Water Framework Directive (2000/60/EC)).

Within the main objective to achieve in this regulation there is the reduction of the pollutant released into the superficial body, the improvement of the status of superficial body for natural and artificial waterbody within 15 years.

Any country should define a monitoring program in which define a coherent and global vision about the water status based on definition of the ecological characteristic of the superficial body, the chemical and ecological actual status and potential. Specifically, in the lake evaluation, at macroscale we must consider biological elements, morphological elements, physic-chemical elements, pollutants, and general elements (Ian J. Allan et all., 2006).

All the analysis defined till now have therefore the aim to understand and classify the status of the water body based on a classification as defined in the Figure 2.2.

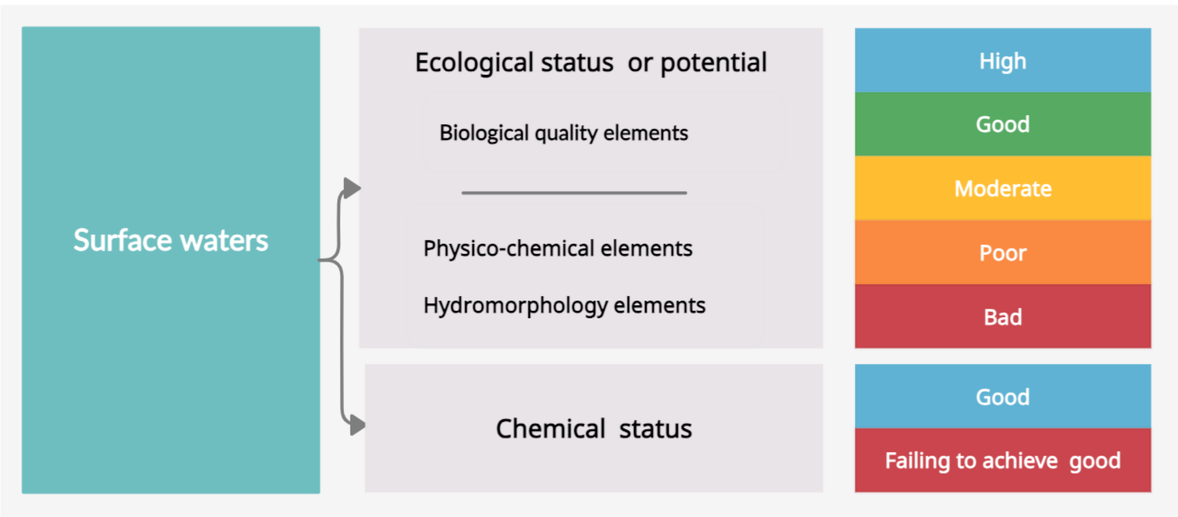


Figure 2.2 *Assessment of status of surface waters according with WDF (source: EEA Report N° 7/2018).*

Focalizing the attention on Como lake, it has been evaluated the status of lake through a monitoring network performed by ARPA from 2014 to 2019 evaluating elements as phytoplankton, macrophyte, phytobentos, macroinvertebrates, and fish fauna. On the other hand, it has been estimated the chemical status. The main substances analyzed were metals, pesticides, PAH, VOC, perfluorinated, phthalates.

From chemical point of view the status of lake is falling to achieve good, while from ecological point of view is moderate. Being the lake characterized by high potential, the goal defined by the region is to reach good status for both ecological and chemical status within 2027 (Fabio Buzzi et al., 2021).

3. MATERIALS AND METHODS

3.1 Description of study area

In this thesis, the idea is to define a method of analysis which could be applied almost to all lakes of Northern Italy, with similar characteristics, to estimate the hydrological balance. Specifically, in this Chapter it is defined the method proposed to analyze a lake, qhile in the Chapter 4, it has been applied to Como lake. It was chosen such lake because one of the largest tributary of Pò river (R.Vezzoli et all., 2014; SUWANU Europe, 2021). The Como lake is regulated, and it is under the jurisdiction of *Enti regolatori dei grandi laghi* or other governments agencies (e.g. ARPA, ENEA, …) which collect data and make some studies.

To perform an accurate geographical contextualization, GIS was used to extract and elaborate satellite images. GIS (geographical information system) is a system which permits to store, acquire, manage, and elaborate geographic information (Cláudia M. Viana et al., 2023). Within more than 1000 applications of the software, in this thesis, the software was used firstly to show the area of analysis and the stations from which data were extracted. After that, DEMs were extracted from Copernicus (F. Hu et al., 2016) and TinItaly 1.1 (Tarquini S. et all., 2023) to elaborate the lake hydro-morphological characteristics using QGIS and SAGA GIS.

To make hydrological modelling and surface characterization, the digital terrain model (DEM) elaboration is very used (Md. Sharafat Chowdhury, 2023). In this specific case it is going to support processing of river basins and other hydrological elaboration.

DEM are terrain digital representations of portion of Earth based on the height of a certain zone with respect to the sea level. For our specific purpose each square mesh in which Italy was subdivided has a resolution of 100 m and it was referred to UTM zone 32, WGS 84. Firstly, the Wang & Liu (Wang L. and Liu H., 2006) tool was used to identify and fill surface depression necessary to remove bias from watershed.

Then after that, hydrological characteristics were extracted: drainage directions and the number of cells. The first determine the direction of water fluxes function of the slope while the number of cells defines values function of areas which contribute to the flux of the hydrological network. These data were necessary to define the watersheds present into the DEM.

Last elaboration performed was the extraction of hydrological channels from watersheds. It was assumed that a channel is formed when a certain area threshold drains to a point.

3.2 Meteo-hydrological data collection and analysis

Initially it has been extracted data series of the main hydrological and meteorological parameters from ARPA Lombardy website taking the longest period available. The data were extracted from a lot of stations and then they were interpolated to get more reliable results and overcome errors present, missing measurements and improve the accuracy of results. For each station were extracted all available data and parameters from 01/08/2008 to 16/04/2023. The choice of this period derives from the longest data period present in stations. Anyway 15 years is a very long period and significant to make elaboration of data.

In case in which there was empty space or wrong values (*e.g.* 999) in the data series, the space was fill through values calculated as the monthly average one.

3.2.1 Hydrometric level

The hydrometric level is the water level with respect a certain measurements station, not always is referred to the sea level.

It is not so important within the hydrological parameters because characterized by high variability due to the variation of the bed of lake, but it could be used through a biunivocal mathematical equation to find the flow rate value.

Data series were extracted from different stations and elaborated. This parameter is referred to the day and its unit of measure is cm.

3.2.2 Temperature

Temperatures extracted and used in this study are always referred to the air temperature.

It has been evaluated the mean, maximum and minimum daily temperatures. All data were extracted from different measurements stations and plotted as daily temperature. All data are measured in °C.

Specifically, for any basin, the temperature has been estimated considering the variation of altitude being the overall watershed at different altitude through a correction parameter. For any station the temperature were estimated using the following formula:

$$T_{i,a} = T_i + b * (z_i - z_a)$$

Where T_i is the temperature measured in the station, z_i the height of the station, z_a is the average height of all stations into the basin and b is a calibrated parameter which correspond to the angular coefficient in the relationship within the height and the temperature.

The average temperature corrected was then calculated with the following formulation:

$$T_m = \left(\frac{\sum_i (T_{i,m} * A_i)}{\sum_i A_i} \right)$$

Where A_i is the area estimated and the same used in the Thiessen method for precipitation estimation.

3.2.3 Precipitation

Precipitation is one of the main parameters used in hydrology to get information about any water body. To make a rough evaluation of it, firstly arithmetic average has been calculated. But this methodology, in the precipitation field, is characterized by a lot of limitations because it doesn't consider the day in which there is no precipitation, and it does not consider the spatial variability of rain. To overcome this limitation then, in addition to this method, precipitations have been plotted using the Thiessen method. The last, also defined as weighted mean method, is based on the subdivision of the catchment into zone with similar area in which at least one station is present. (Lin Arianti et all., 2018). The area was subdivided into zone through imaginary lines and in any zone, the precipitations were interpolated as the weighted amount of daily rain using the formulation below. This method was preferred with respect to the arithmetic one because it considers the spatial variability of the rain:

$$P = \frac{\sum AiPi}{\sum Ai}$$

Where Pi is the rain from a single measurement station while *Ai* is the area under the considered station.

The area of the lake was subdivided into areas through the usage of GIS (Geographic Information System). Also, in this case precipitations were extracted from ARPA website from large number of different stations. All data were referred to a daily precipitation and its unit of measure was mm.

It is important to underline that all values of precipitation used in the calculation derive from the application of Thiessen method. It has been neglected the impact of the altitude in the precipitation measurements.

3.2.4 Evapotranspiration

Evapotranspiration (ETP) is a process in which transpiration performed by plants and evaporation of the water occur simultaneously. These processes are strongly influenced by the fraction of solar radiation which reach the soil. In particular, the sum of the two processes, evaporation, and transpiration, are going to transfer large amount of water from the land or water basins to the atmosphere (Richard G. Allen et all.; 1990).

From the above knowledge of mean temperature and mean extra-terrestrial radiation (Ra), it was possible to estimate through the empirical (temperature based) method of

Hargreveas-Samani the ETP. Despite the calculation through this formulation gives a values of reference crop evapotranspiration, anyway the method gives a representative expression for potential evapotranspiration, and it could be used with this purpose. The below formulation was used:

$$ETP = 0,0022 * Ra * \sqrt{\partial T} * (T + 17,8)$$

Ra is the mean extra-terrestrial radiation (mm/day) which is function of latitude, ∂T is the temperature difference (mean monthly maximum temperature – mean monthly minimum temperature °C) and *T* the mean air temperature (°C).

In particular, Ra is the extra-terrestrial radiation which corresponds to the radiation incident on the surface tangent to the outer surface of the atmosphere. It is function of zenith angle, latitude, time, and number of days. It has been calculated day by day and then found the average monthly value to calculate the evapotranspiration parameter (Y.O. Krivoshein et all., 2020). The formulation used for the calculation of extra-terrestrial radiation is represented below (John E. Hay, 1979):

$$Ra = \frac{24 * 3600}{\pi} G_{sc}(1 + 0.033 * cos\frac{360n}{365})(cos\varphi * cos\delta * sin\omega_s + \frac{\pi\omega_s}{180} * sin\varphi * sin\delta)$$

Where G_{sc} is the solar constant equal to 1367 W/m^2, φ represents the latitude, δ is the declination of the Earth and ω_s is the hour angle.

The hour angle has been evaluated measured in degrees where 24 hours correspond to 360°. Then any hour angle is equal to $(360/24)° = 15°$. From hourly values of *Ra*, the daily one has been estimated through the mean values.

The annual ETP value was compared with the one extracted from ISPRA through the application of the model BIGBANG.

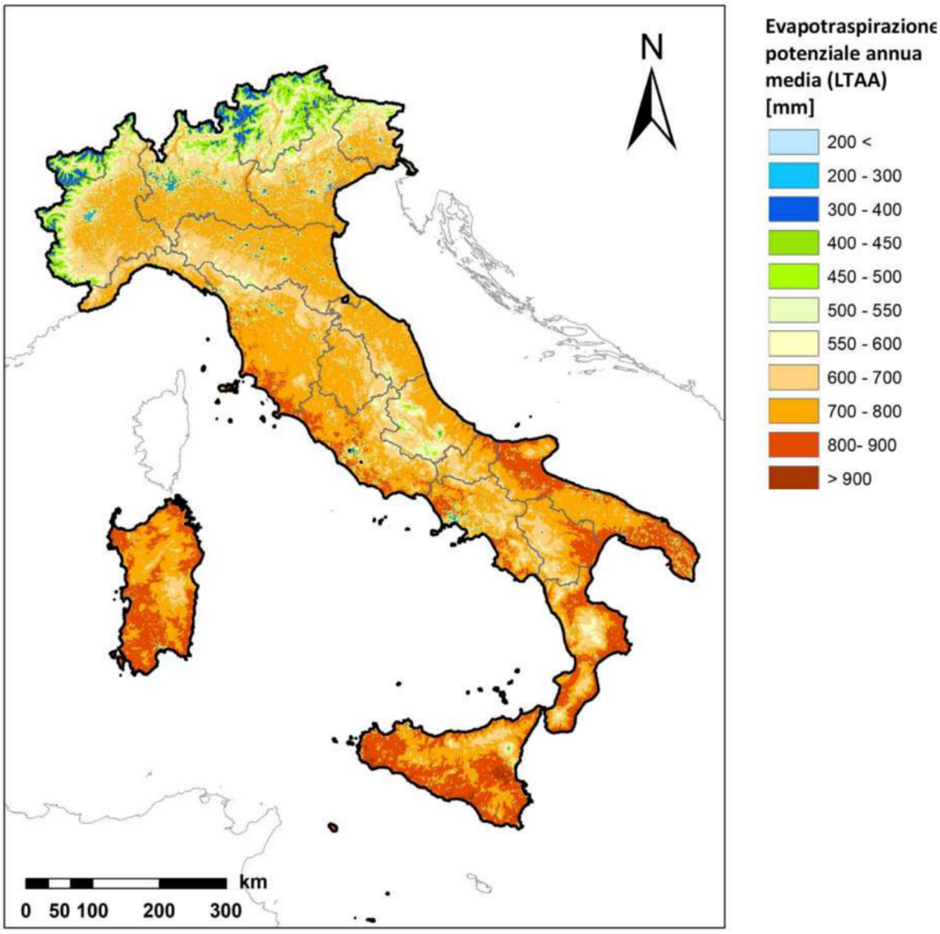


Figure 3.1 *Annual average ETP in the world from ISPRA BIGBANG model application.*

And from the above image is visible how the value for what concern the zone of Pò district (North-West Italy) is around 630 mm/year. Additionally, it was compared for each monthly average values get from BIGBANG with the ones get from the empirical formulation application (ISPRA, 2021) to estimate the goodness of estimation.

The above calculation of ETP was used to estimate the phenomenon of evaporation and transpiration in all the watershed considered except in the lake where it has been calculated the evaporation through another formulation.

The lake evaporation was estimated using the Penman formula (Edward T. Linacre, 1977):

$$E = \frac{\dfrac{700\,T_m}{(100-\varphi)} + 15(T - T_d)}{(80 - T)}$$

Where $Tm = T + 0.006 * h$ where h is the lake elevation (m) with respect to the sea, T the temperature of the day (°C), φ the latitude (degrees) and T_d the mean dewpoint (°C).

Specifically, the term $(T - Td)$ has been calculated using the empirical formulation from Linacre method very useful for long interval of time as in this case:

$$(T - T_d) = 0.0023h + 0.37T + 0.53T_{mean} + 0.35T_{ann} - 10.9$$

Where T_{mean} is the monthly mean daily temperature (°C) and T_{ann} is the mean temperature of hottest and coldest months (°C).

The above method provides a good estimation of the lake evaporation despite it does not consider the wind function and included the aerodynamic component from the latent heat point of view (Mostafa Ali Benzaghta et all., 2011).

This formulation was assumed valid only for the lake part being in that zone the transpiration equal to zero.

3.2.5 Discharge

Discharge is defined as the amount of water which pass through a section within the time t. Generally, this parameter is calculated and not measured because very complex to measure (Binh Pham-Duc et all.; 2020). Not being present a recent database containing these data, they were estimated through the stage discharge method. Specifically, these relations were given by ARPA in according with rivers hydrometric levels. Discharge could be subdivided into surface and groundwater flow. The last (flow within saturated zone) is the most difficult and uncertain parameter to estimate, this is the reason why was estimated later using the hydrological balance, while the discharge was estimated through the stage-discharge method and the application of HBV model (Mikdat Kadioglu and Zekai Sen, 2001).

About the stage-discharge method used to estimate Q data series, it was possible to make such kind of evaluation starting from the hydrometric level knowledge and the relationship which exist between these 2 quantities for any river:

$$Q = f(h)$$

Stage discharge curves were referred to the 2 main inlet rivers and the Adda outlet river. These relationships were established by making a few relevant numbers of observations of stage and discharge and their relation over a defined period of time at the river gauging section. Despite it is not only function of these quantities, to make the correct estimation it was assumed that there were not additional variables (Muthiah Perumal et all., 2007; J.Leonard et all.; 2000).

For any rivers points were used lots of rating curves for discharge elaboration; not only referred to recent years discharge but also with discharges coming from hydrological yearbook. Final values of Q both for inlet and outlet points of lakes were extracted through the average between values get from application of different rating curves. More than one values for each point was calculated to reduce the uncertainties given mainly by roughness and exponent values (P. Claps et all., 2003).

3.2.6 Change in storage and hydrological balance

In order to estimate the hydrological balance, the change in storage parameter has been estimated knowing the lake surface equal to 145 km^2 and the mean monthly hydrometric level. Change in storage is a very interesting parameter because is going to define and permits to understand the water cycle into a catchment (Min Xu et all.; 2013).

The estimation of volumetric water balance was necessary to estimate the sub-superficial component present into lake and the error associated to the calculation and estimations.

In this specific case the hydrological balance has been applied to get the groundwater component (g) which contain also the error associated:

$$g = Q_{in} - Q_{out} + P - E - ETP - \frac{dS}{dt}$$

Where P represents precipitation, E potential evaporation from lake, ETP is the potential evapotranspiration from the overall basin (except the lake), Q_{out} the runoff which corresponds to the amount of water which goes out from the lake while Q_{in} is the amount of water that goes into the lake and dS/dt the change in storage.

The water balance could be defined as the water assimilated and lost from the water body. It is going to represent the water cycle of a catchment and it is very useful to understand hydrological processes. The water balance is the main estimation that could be performed in hydrology because it is able to define e describe how the water components are going to be subdivide and how they act along the water cycle (Mary Nichols, 2007).

Evapotranspiration term was subdivided into the 2 components to understand additionally in which measure the 2 phenomena act. In particular the evaporation is almost referred to the water present into the lake while with the part related to transpiration (and evaporation too) was defined the amount of water released by plants present in the catchment (Shan Huang et all., 2023).

3.3 Statistical data analysis

The aim of this paragraph is to make evaluation of data series using statistical analysis, necessary to improve the quality of data and with the capability to make more reliable the interpretation of results (Jessica Sendef and Arryn Robbins, 2019).

Statistical analysis was performed for any measured parameters coming from the merge of different measurement stations. Statistical analysis was performed through the usage of the software developed by ISPRA ANABASì. These statistical analyses were performed before any additional calculation and application of models to get more accurate conclusions (WMO, 2003). It was applied this statistical analysis to our data to understand if our series were homogeneous (being the fluctuations in series due only to natural variability of climate), stationary (because constant in the structure in term of mean and variance) and the recording period used enough long for analysis purpose (Renata Vezzoli et all., 2012).

3.3.1 Statistical analysis characterization

At the extracted past data was performed statistical analysis to get general information about series. All used data were extracted from different measurements stations and elaborated. The aim was to remove the outliers and the missing data. In the last case, the empty data was filled through average monthly values. All periods of time with missed data longer than 20 days were left empty to make series more robust. Since the hydrological data doesn't follow generally a Gaussian distribution and due to the presence of outliers, series were characterized by median and percentiles (Yuanfang Chen et all., 2022).

To better describe series from statistical point of view, some indexes have been evaluated:

- Position index to define the tendency of data;
- Variability index to define the dispersion of data with respect to average values;
- Shape index which describes the shape assumed by data compared with the one expected.

About the position index it was evaluated the mean and the median. The mean is defined as:

$$m = \frac{1}{N}\sum_{i=1}^{N} Xi$$

While the median is the central value of the data series and correspond to 50% in the percentile.

Additionally, as a position index, it was evaluated all percentiles and quantiles. The minimum and maximum value are going to represent respectively percentiles at 0% and at 100%.

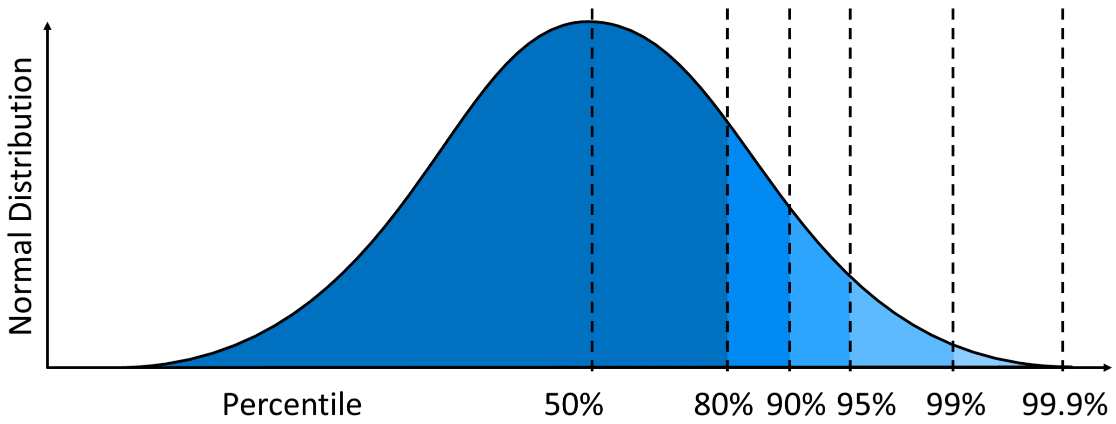


Figure 3.2 *Normal distribution representation and its percentiles.*

Within the position index, additionally the percentile at 25% and 75% have been calculated with the aim to know the position that these values occupied into the data series.

About the variability index, it has been calculated the variance, the standard deviation, the interquartile range, the variation coefficient, and the range of values variation. All these parameters define the way in which our data series differ among them and with respect to the distribution's center.

Variance is the standard deviation with respect to the sum of standard deviation itself divided by the number of samples minus one:

$$s^2 = \frac{1}{N-1}\sum_{i=1}^{N}(Xi - m)^2$$

The mean square root or standard deviation is the square root of the variance:

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(Xi - m)^2}$$

The range measure the maximum amplitude of the sample:

$$R = Xmax - Xmin$$

The IQR (inter quartile range) is a robust index used to measure the data distribution:

$$IQR = Q3 - Q1 = P_{75\%} - P_{25\%}$$

Additionally, within variability index, it was evaluated the coefficient of variation CV which represents the normalized series with respect to the mean:

$$CV = \frac{s}{|m|}$$

Last type of index calculated is the shape index in which the asymmetry and Kurtosis have been calculated. These indices are going to give information about the shape of data distribution.

Asymmetry index or skewness measure the no-symmetry of the series; in fact, if its value is zero the series is symmetrical. Generally, all the hydrological data present a positive asymmetry.

$$g = \frac{\frac{1}{N}\sum_{i=1}^{N}(Xi - m)^3}{\sqrt[3]{\frac{1}{N}\sum_{i=1}^{N}(Xi - m)^2}}$$

Kurtosis index represents how much far is the distribution of data from the normal distribution; in fact, in case in which the distribution follows the Gaussian one, this parameter is equal to zero:

$$k = \frac{\frac{1}{N}\sum_{i=1}^{N}(Xi - m)^4}{\sqrt[2]{\frac{1}{N}\sum_{i=1}^{N}(Xi - m)^2}} - 3$$

After that, through the explorative analysis, it was evaluated visually the presence of outliers, trend, temporal change, and so on. So, in addition to the above parameters it has been draw some graphs related to the frequency distribution of values and the cumulative frequency distribution which represents the distribution of all data.

3.3.2 Basic hydrological statistical analysis

After statistical analysis characterization, the basic hydrological statistical analysis was performed with the aim to evaluate:

- The autocorrelation of data;
- Stationarity of data (seasonal component and trend);

The autocorrelation is going to define the linear dependency degree within data values of series, and it is defined using the Autocorrelation function ACF:

$$\rho[k] = \frac{Cov\ [k]}{Cov\ [0]}$$

Where *k (lag)* is the temporal interval within elements of series. In according with the value of ρ it is possible to understand the correlation that exists between 2 parameters and their dependency.

Since the hydrological series should be based on a stationarity (it does not change in time), at this point, analysis to verify such condition were done with the aim to confirm that all series come from the same population. In this thesis if there will be the presence of some no-stationarity conditions they will be corrected only in case in which result significant variations to compromise the analysis through the usage of interpolate values (Daniel A.Griffith, 2019).

To understand the seasonality of data and then to know the homogeneity and stationarity of series the below parameters have been evaluated with the aim to understand if series were good to apply models or not.

Seasonal variability is linked with the evolution of monthly weather. To understand the presence of variations and then the evolution of series during the year, it has been evaluated mean values and then, they were compared with results get from the application of LOESS methods (Locally Weighted Scatterplot Smoothing method). LOESS is a time series decomposition that separates time series into 3 components: trend, seasonal and remainder. The trend component captures the long-term changes in the data, the seasonal component captures the repetitive patterns that occur within a year, and the remainder component represents the random variation or noise in the data. Specifically, the application of this method permits the removal of noise with respect to the standard method to permits a better understanding of seasonality (Zhongcheng Cao & Teng Wang, 2022).

Later, it was considered and evaluated the presence of trend and how much it was significative. To understand and evaluate the variation, linear regression was performed based on Pearson coefficient test. In case there was present a trend, if this variation was "slow" anyway the series was considered as stationary and then analyzable. (Dagnew Yebeyen et all., 2022).

3.4 HBV model

HBV is a conceptual rainfall-runoff model which permits to make diagnosis and get information about the characteristics of rainfall and runoff (Marzena Osuch et all., 2019).

The software was used with the aim of extent discharge data series for the inlet rivers due to the shorter period present. The idea was to model discharge values from the already estimated one using the stage-discharge curve.

HBV is a conceptual model which require as input only few parameters as precipitation, temperature and ETP. It is requested areal precipitation that have been calculated through

Thiessen method and ETP estimated using the method of Hargreveas. Last parameter was corrected with the below formulation as request in the handbook (Jan Seibert, 2005):

$$Epot(t) = \left(1 + Cet(T(t) - Tm)\right)Epot,m$$

Where *Epot,m* is the long-term mean evaporation (mm/d), *T(t)* is the temperature at the day (°C), *Tm* is the long-term mean temperature for that day of the year (°C), *Cet* is the correction factor (1/°C).

The main output will be a comparison between simulated daily streamflow and observed. The aim is to model the catchment runoff at different condition and under different type of catchment characteristics and model setting.

Basically, the model work following the flux represented into the Figure 3.3, which from input data as a precipitation, ETP and temperature define and suppose a snow routine and soil moisture routine based on a set of 15 parameters. Then the software is going to elaborate the response function till find the final runoff.

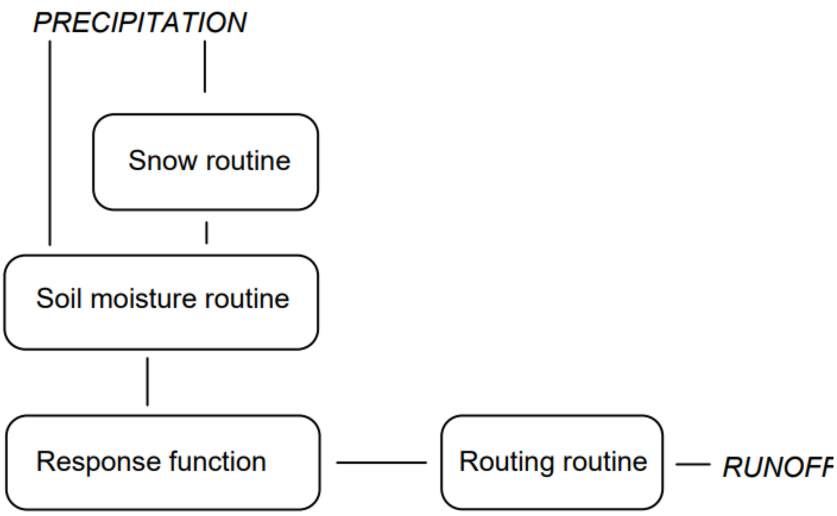


Figure 3.3 *HBV model representation.*

Before to start with the model, the first step was the calibration. The calibration of the model was performed using the GAP optimization tool (Genetic Algorithm and Powell) present into the software. Such type of optimization starts from random population of main hydrological parameters (defined into the Table 3.1) and it is going to make continuous run of model till reach the value of objective function to have the best possible goodness of fit (Tomasz Spalek et all.; 2005).

Table 3.1 *HBV model calibration parameters.*

Parameter	Symbol	Unit
Threshold temperature	TT	°C
Degree-day factor	CFCMAX	mm/°C d
Snowfall correction factor	SFCF	-
Refreezing coefficient	CFR	-
Water holding capacity	CWH	-
Maximum of soil moisture zone	FC	mm
Threshold for evaporation reduction	LP	-
Shape coefficient	Beta	-
Recession coefficient (upper stor.)	K0	1/d
Recession coefficient (upper stor.)	K1	1/d
Recession coefficient (lower stor.)	K2	1/d
Threshold for K0 to become K1	UZL	mm
Maximum percolation	PERC	mm/d
Routing parameter	MAXBAS	d
Correction factor for potential evapotranspiration	CET	1/°C

The model was run considering for the calibration the longest available period of time and the objective function expected was $Reff = 1$. In the application of this model, it has been assumed that the catchments coincide with the ones defined in the DEM.

In the run of the model, the catchment was modelized assuming characterized by an outflow and boxes how represents in the Figure 3.4 below:

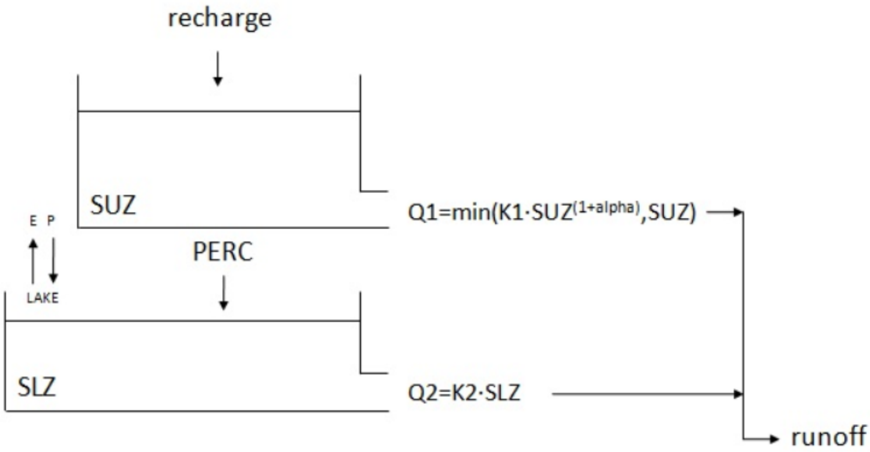


Figure 3.4 *Representation of standard HBV model used in the calculation.*

Where *recharge* is the input from soil routine (mm/Δt), *SUZ* the storage in the upper zone (mm) while *SLZ* in the lower zone (mm). *PERC* is the maximum percolation (mm/Δt), K_i the recession coefficients (1/Δt) and Q_i the runoff components (mm/Δt).

In the model, the precipitation is divided within rain and snow in according with the value of TT multiplied for SFCF using the degree day-method:

$$melt = CFMAX(T(t) - TT)$$

Rainfall and snowmelt are divided into water filling the soil and groundwater recharge depending on the relation between water content of the soil box and its largest value. PERC (mm/d) defines the maximum percolation rate from the upper to the lower groundwater box. Runoff from the groundwater boxes is computed as the sum of two or three linear outflow equations depending on recession coefficient. This runoff is finally transformed by a triangular weighting function defined by the parameter MAXBAS to get the simulated runoff (mm/d) (T.L.A.Driessen et all.; 2010).

R_{eff} is going to represent the efficiency of the model and the parameter was set to calibrate the model. In particular, if its value is equal to 1 it is going to indicate a perfect fit of the objective function:

$$Reff = 1 - \frac{\sum(Qobs - Qsim)^2}{\sum(Qobs - \overline{Qobs})^2}$$

Despite very small set of parameters available, anyway almost all of them was used for the calibration phase (Hamza Ouatiki et all., 2020). Only one year of data, for any river were removed and used for the validation phase. The validation is a process which verified that the accuracy of model and of system are respected. More the model is close to the system and better is the model generated. A simulation is not validated in case in which the difference between the measured values and simulated ones is greater than the amount that is willing to tolerate (Husam Baalousha, 2008).

To estimate the validity of calibration and validation performed into hydrological series, additionally to *Reff* parameter, KFG has been estimated. This was performed because the first does not consider the trend of values (Guglielmo Petrobon, 2022). Specifically, the Kling-Gupta efficiency parameter is represented below:

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha - 1)^2 + (\beta - 1)^2}$$

$$r = \frac{Cov_{c,o}}{\sigma_{s*}\sigma_o}$$

$$\alpha = \frac{\sigma_c}{\sigma_o}$$

$$\beta = \frac{\mu_c}{\mu_o}$$

Where μ is the mean of values, σ the standard deviation, *Cov* the covariance, the letter “o” means observed while “c” calculated. This parameter could be negative or positive but in any case lower than 1. More this parameter is close to 1, close are the trends of series compared.

4. RESULTS

4.1 The Como lake contextualization

Como lake is the third largest lake in Italy. It is subdivided into two branches and only in one side the outlet is present and regulated by a barrage in Olgiate, Lecco branch. The aim of the barrage is to regulate the outflow to avoid flood in cities, but it is also used to regulate the water which feed hydropower plants and used for irrigation channels (Tewelde Hagos Gebremedhin et al., 2022).

The lake is managed by Consorzio Adda. Its surface is 145 km^2 and the overall average water volume is around $165.3(10^6)$ m^3 evaluated from historical series (from 1946 to 2022). [*Enti regolatori dei grandi laghi*] The lake is within Italy and Switzerland, and it is one of the main feeders of Po' (Flavia Fuso et al., 2021). It is the deepest Italian lake with average deep of 161 m.

The lake is feed mainly by Mera and Adda rivers and a lot of other channels. The lake fed Adda river through the dam. A lot of water that reach the lake derives from the snowmelt runoff too. Mera's basin area is going to extend for the overall valley of Chiavenna within Italy and Switzerland. For what concern the Adda basin, it is entirely developed in Italy and the river begin in Bormio (Renzo Rosso, 2004).

The portion of lake and its watershed was extracted in form of DEM. Below there is a comparison between the DEM as downloaded and its elaboration with QGIS to get the height in according with the color variation.

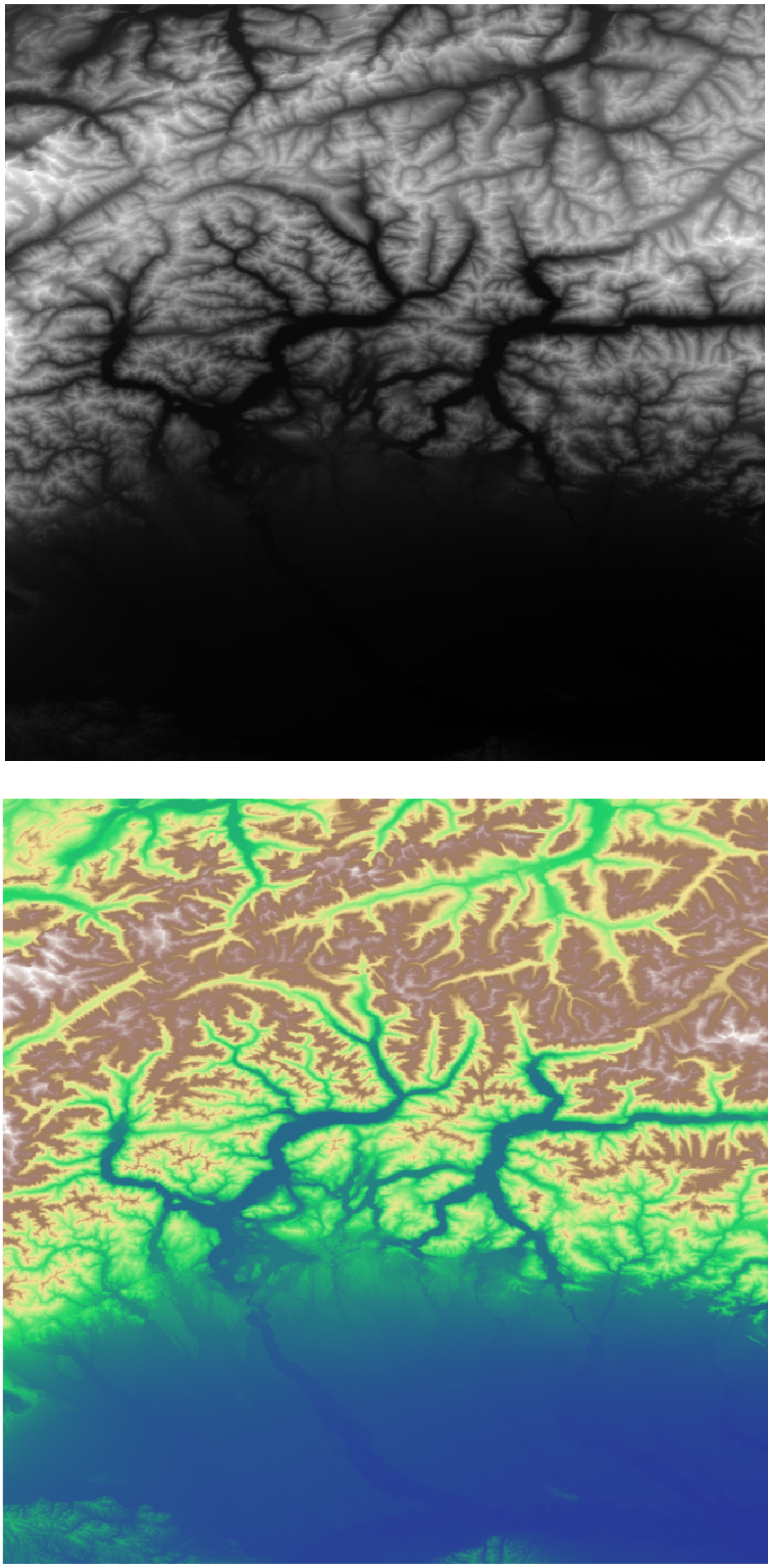


Figure 4.1 *Original (above image) and elaborated DEM (below image).*

From the above Figures were possible to see the connection within channels and lake. Specifically, were visible a possible connection within Como lake and Lugano lake. To understand if there is a hydraulically connection within the 2, drainage directions analysis was performed. In the Figure 4.2 there is the zoom of the zone with the possible connection.

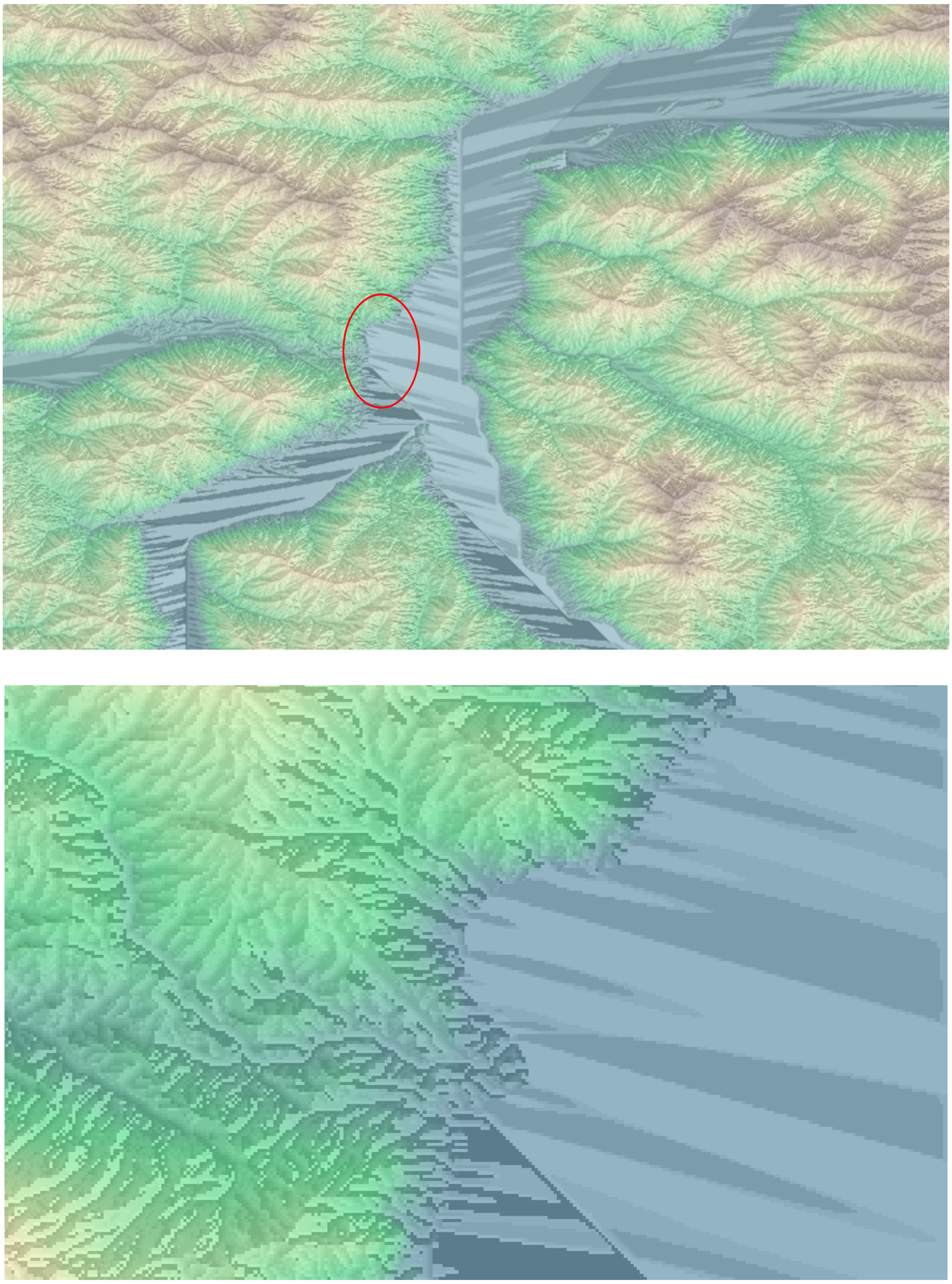


Figure 4.2 *Representation of drainage direction details.*

From the Figure above, it is present a ridge within the lakes. This means that there is not hydraulically connection within them. So, the Lugano lake is not a tributary of Como lake and therefore will not be considered into the following evaluation.

Additionally, the DEM was elaborated through the usage of SAGA program. Firstly, it has been extracted the 3 basins used in the following analysis. The orange one is the Como lake watershed while the other 2 are basins which contain tributaries of lake. Specifically, the blue watershed is the one which contain Mera river while the red one the Adda.

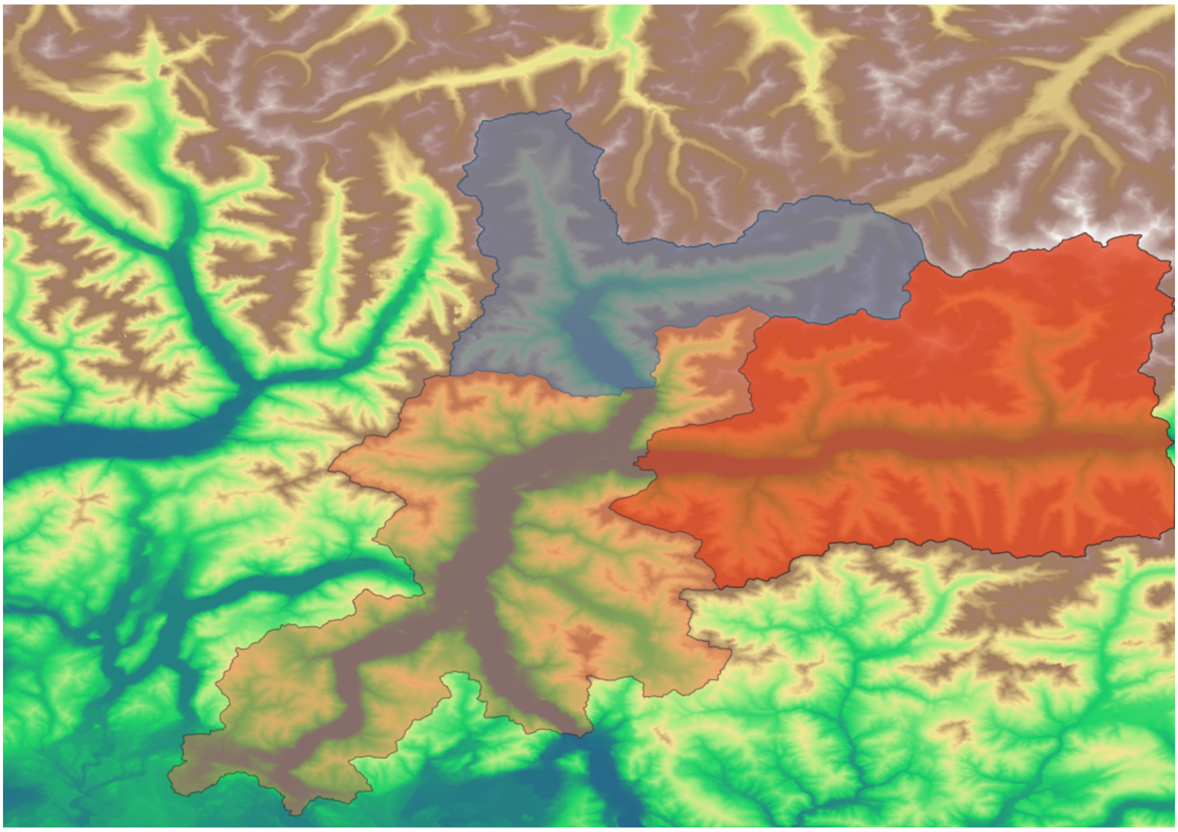


Figure 4.3 *Watersheds representation.*

From GIS was extracted some geometrical characteristics of basins:

Table 4.1 *Basins geometrical characteristics.*

	Area (km^2)	**Perimeter (km)**
Como lake basin	1859,44	347,21
Adda basin	1830,71	282,16
Mera basin	861,35	154,62

Last elaboration performed with GIS was the extraction of channel network assuming that any channel is formed when a certain area threshold drains to a point. Specifically, that threshold was chosen in according with the number of cells present in the DEM.

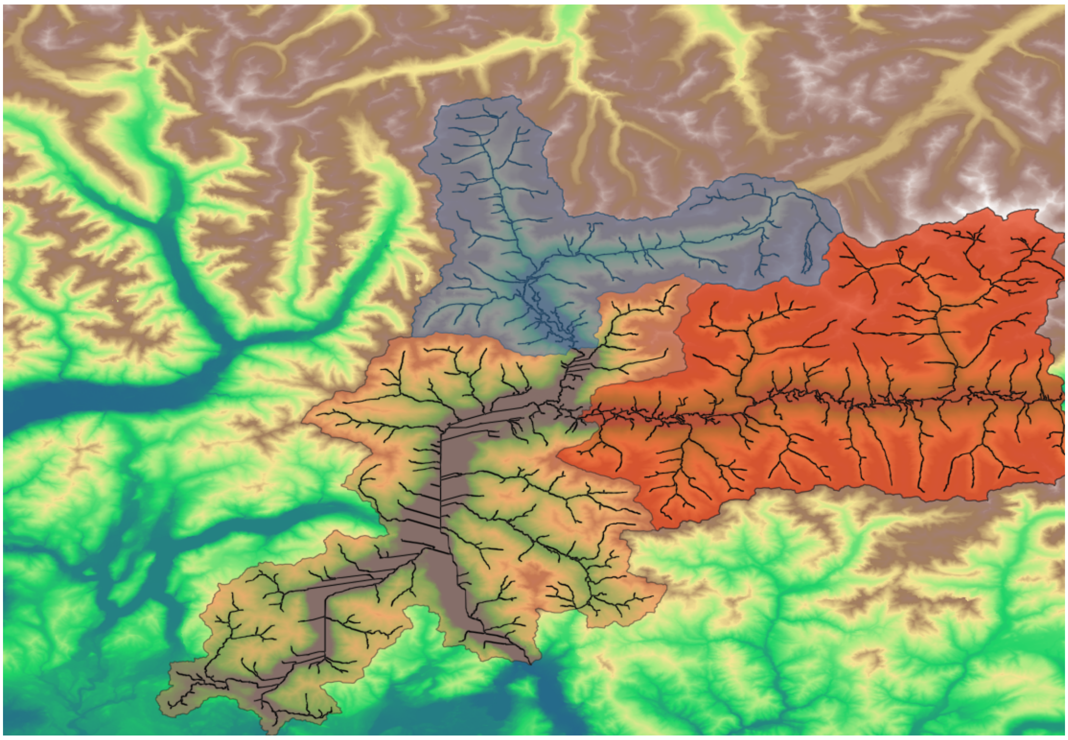


Figure 4.4 *Channels representation.*

At this point, historical series of meteo-hydrological data have been extracted from ARPA Lombardia which is the main regional agency for Environmental protection. A lot of different measurement stations were considered with the aim to extract a lot of data and reduce the error associate to them (e.g., temperature, precipitation, hydrometric level, humidity, and energy radiation). Not all the series are long the same period, so this is another reason why a lot of measurement points were considered. The longest measurement period was 22 years of data. Anyway, all data considered in this study and analyze was reported to the same period from 2008 to 2023. Starting from extracted data, it was calculated additional parameters as: ETP, discharge, change in storage and applied the hydrological balance.

In the Figure 4.5 it is represented all measurement stations from which was extracted the data related to Como lake basin. For any stations more than one parameter was extracted as represented in Table 4.2.

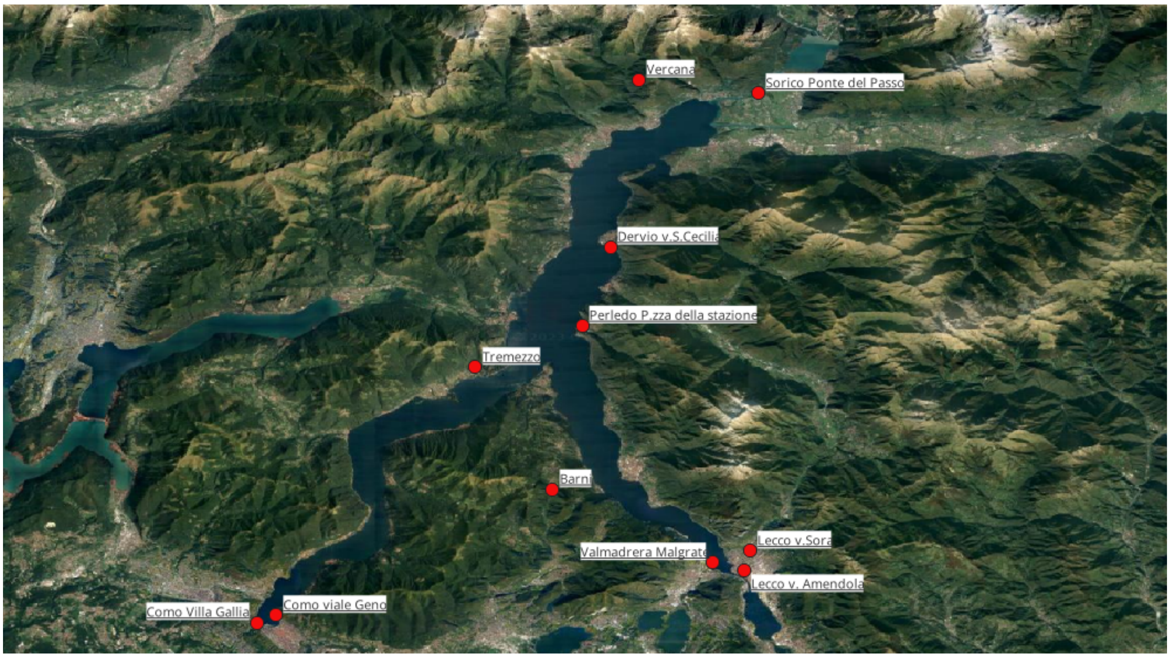


Figure 4.5 *Measurement stations in Como Lake basin.*

Table 4.2 *Measurement stations characteristics.*

Name of station	Coordinates	Measured parameters
Barni	45.905271, 9.266101	Relative humidity, temperature and precipitation.
Como viale Geno	45.820254, 9.079902	Precipitation, temperature and hydrometric level.
Como villa Gallia	45.815042, 9.066971	Temperature, precipitation, wind and relative humidity.
Dervio V.S. Cecilia	46.068961, 9.305364	Temperature, precipitation and relative humidity.
Lecco v. Amendola	45.850191, 9.395577	Precipitation and global radiation.
Lecco v. Sora	45.863748, 9.399950	Precipitation, temperature, relative humidity, wind and global radiation.
Perledo P.zza della Stazione	46.015828, 9.286409	Precipitation.
Sorico Ponte del Passo	46.172711, 9.405111	Hydrometric level.
Tremezzo	45.987716, 9.214075	Precipitation, temperature and relative humidity.
Valmadrera Malgrate	45.855860, 9.374633	Hydrometric level.

Vercana	46.181842, 9.324676	Temperature, wind, hydrometric level, global radiation, relative humidity and precipitation.

For what concern the hydrological level, it has been measured 3 points in the lake. Specifically, the zero level was found around 200 m except in Como where the hydrometric level was set equal to 222 m. The variation in the hydrological level in Como is due to the hydrometer that moved in the time to contrast the subsidence which interest the zone (Greta Bajni et all., 2018; Valerio Comerci et all., 2007). The phenomenon of subsidence could be due to natural causes (plate-tectonic activities, isostatic adjustment, sediment load,..) or anthropic (fluid extraction, vibrations, explosions,..) (Dirk Doornhof et all.; 2006). For this specific case, both causes produced a subsidence; during the last century this phenomenon was enhanced by larger extraction of fluid.

The stations have been chosen along the Como lake to avoid additional errors in parameters due to the height variation.

4.2 Analysis of meteo-hydrological parameters

4.2.1 Analysis of hydrometric level

In the Figure 4.6 it is plotted the average variation of hydrometric level in Como Lake from 2008 to 2023, and it is visible how in the last years, starting from 2015 almost, oscillations become larger. In these last years are also present the smallest and largest hydrometric level.

Little variation in the hydrometric level reference have been found within the hydrometers, but all of them have been reported at the absolute hydrometric zero level equal to 197,37 m a.s.l. (*Enti regolatori dei grandi laghi*).

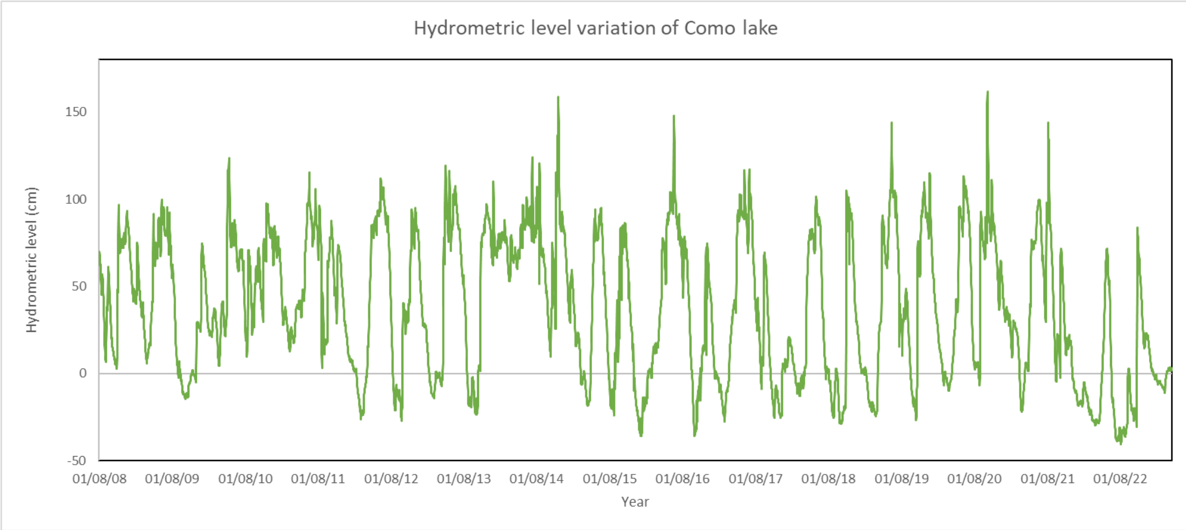


Figure 4.6 *Daily hydrometric level variation.*

Positive and negative level variations are present because values are evaluated respect to hydrometric level which differ from the absolute level zero considered in the lake. The largest negative values are during summer and at the beginning of spring where larger amount of water is required for irrigation. These conclusions are better visible in the Figure 4.7.

Looking at the daily hydrometric level variation, 5 peaks are present related to heavy rain period, in particular the highest value of hydrometric level is equal to 161.8 cm in October 2020. On the other hand, in August 2022 are present lowest values of hydrometric level. Maxima and minima values present in the last years are going to represent how the effect of climate change are going to become more strongest influencing the level of the lake.

Additionally, it was plotted the monthly hydrometric variation of the lake considering the same interval of years:

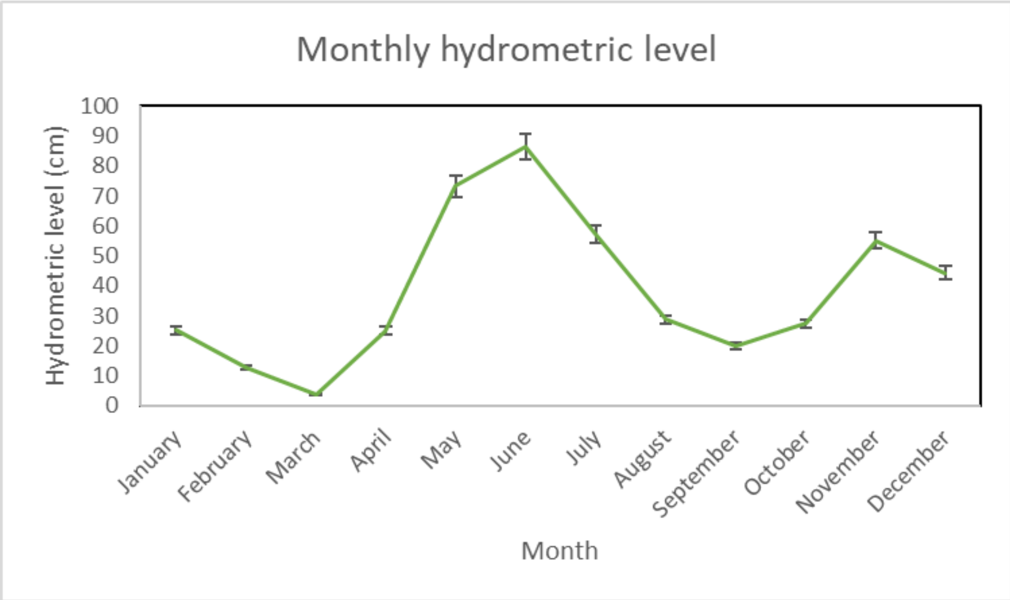


Figure 4.7 *Mean monthly hydrometric level variation.*

Due to large amount of rain and snowmelt, the highest hydrometric level is from May to July. On the other hand, during summer are present the lowest level of water due to low amount of rain but also due to large release of water into the Adda river for agricultural purpose and electrical energy production.

In the above figure has been considered the standard deviations of the values being the values related to more than one year. The largest variability in values is present on May, June, July, November, and December. This is because in these months larger is the oscillation of values.

For what concern the hydrometric level, generally it is not so important within the hydrological parameters because characterized by high variability, but it could be used through a biunivocal mathematical equation to find the flow rate value as done in this case.

For this specific case, it is important to underline that the hydrometric level variation, it is partially due to the meteorological parameter but mostly it is controlled by dam present in Valmadrera station.

In the figure below it has been plotted the values of hydrometric levels in the inlet points and at the outlet point of the lake (Malgrate Valmadrera station) to evaluate better the presence of some delay or peaks.

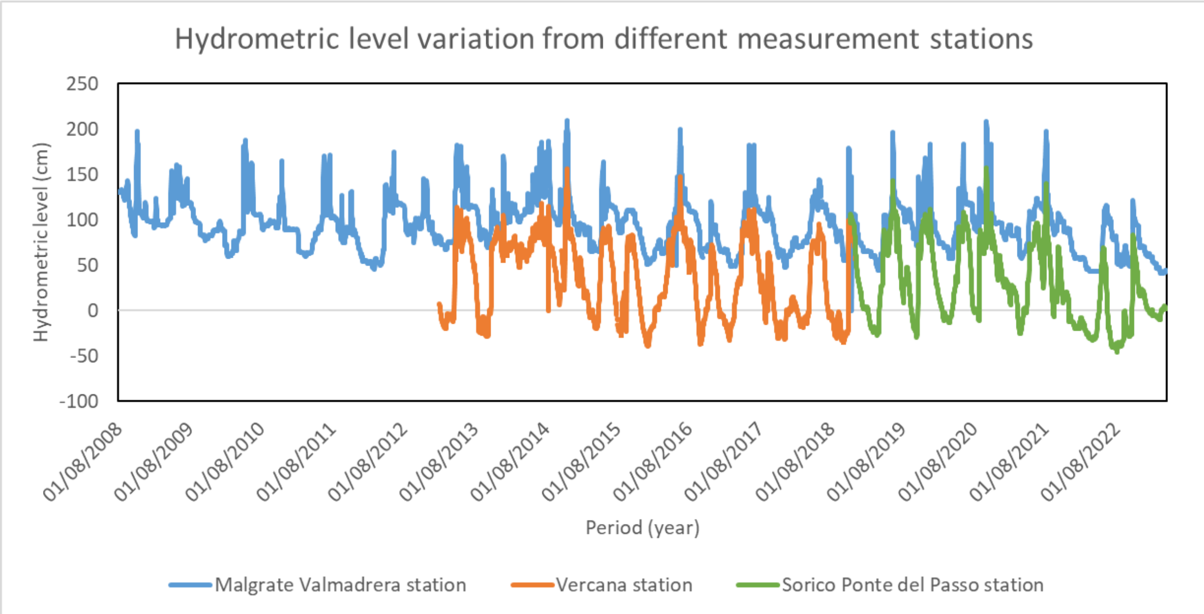


Figure 4.8 *Hydrometric level comparisons from different measurement stations.*

From the Figure 4.8 is represented the hydrometric level from outlet point of lake (blue line) and the 2 inlet points which derives from 2 different rivers (Adda – orange line and Mera – green line). It was not possible to extract the overall series for the inlet rivers; this is the reason why later their discharges have been forecasted using HBV software.

4.2.2 Statistics of hydrometric level

From statistical point of view, through the usage of the software ANABASì it was analyzed the hydrometric level in term of frequency variation in time.

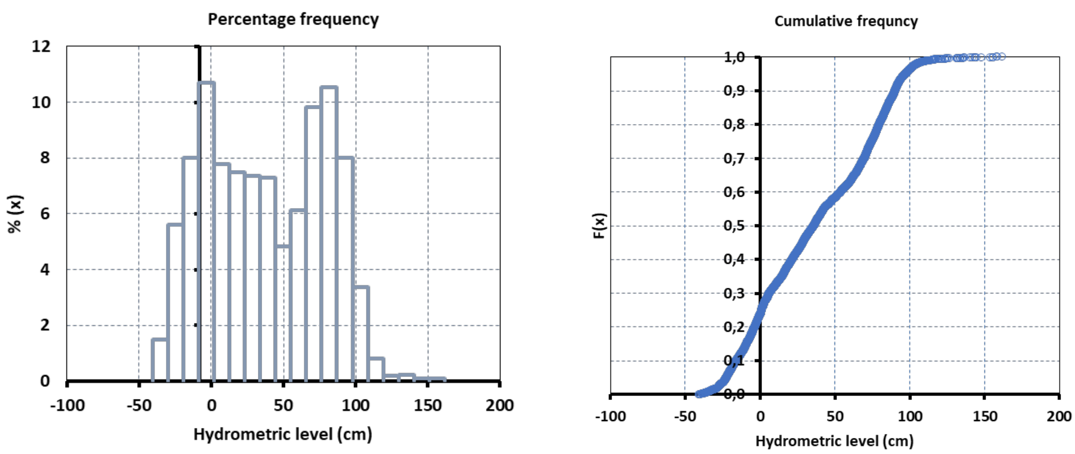


Figure 4.9 *Percentage frequency (left) and cumulative frequency of hydrometric level (right).*

The above Figure represents in term of percentage and cumulative frequency the lake water level. Largest values of hydrometric level along the series occurs from -10 to 0 cm and from 70 to 90 cm.

In the table 4.3 are represented all univariate statistical parameters which are going to describe the series of hydrometric level.

Table 4.3 *Statistical analysis characterization results.*

Statistic	Value	Symbol
Position index		
Mean	37,87	m
Minimum (percentile 0%)	-40,80	min
1st quartile (percentile 25%)	1,15	Q1
Median (percentile 50%)	36,00	Q2
3rd quartile (percentile 75%)	74,80	Q3
Maximum (percentile 100%)	161,77	max
Dispersion index		
Inter quartile range (Q3-Q1)	73,65	IQR
Range (max-min)	202,57	R
Standard deviation	40,5	s
Variance	1642,9	s2
Variation coefficient	1,1	CV
Shape index		
Asymmetry	0,006	g
Kurtosis	-1,2	k

From the Table 4.3 is possible to understand how hydrometric level is asymmetric due to the value of asymmetry close to 0.

At this point, the temporal dependency within measures was extracted (through the autocorrelation function) and then it was evaluated the presence of trend and seasonality to describe the behavior of data series.

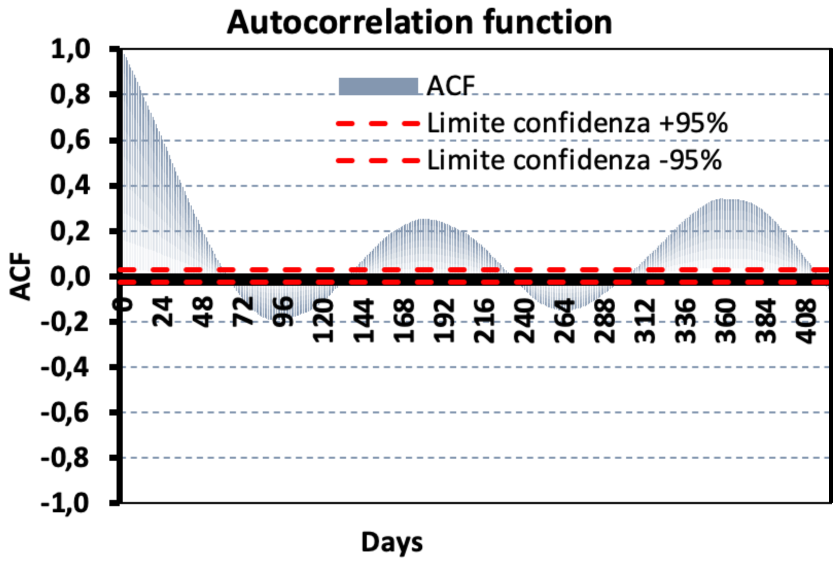


Figure 4.10 *Autocorrelation function for the hydrometric level.*

It could be afforded that it exists a correlation within considered data. Specifically, the correlation is maxima in the initial months and later decreases, but it is anyway present along all period of time considered. As a consequence, it is possible to proceed with others statistical analysis to evaluate the presence of seasonality, and trend with the aim to characterize the series in a univocal way.

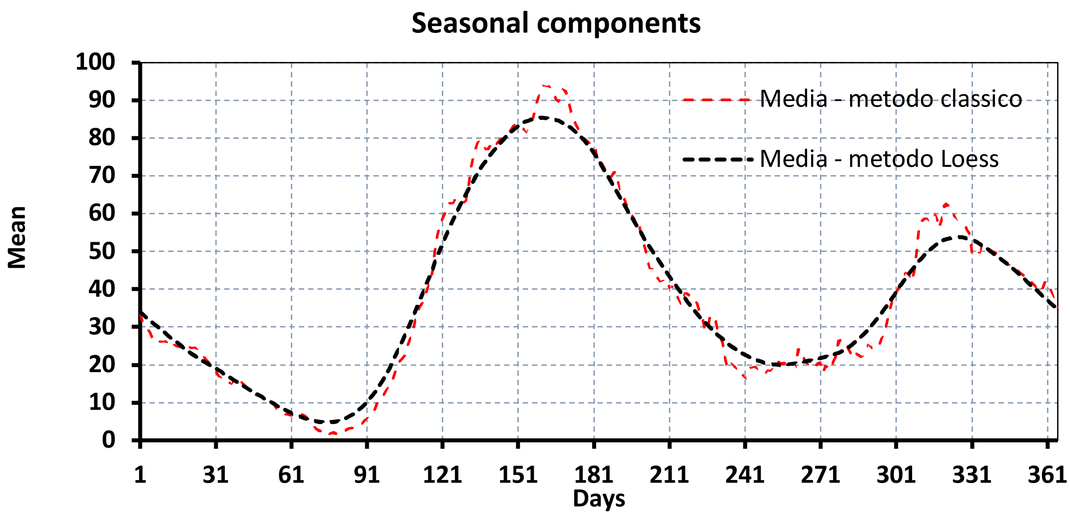


Figure 4.11 *Seasonal component of the mean of the hydrometric level.*

The seasonal variation with any method used presents a peak during the spring-summer season and later in the last 3 months of the year. So, a strong seasonal component is present.

Secondary, the presence of a trend in the series was evaluated:

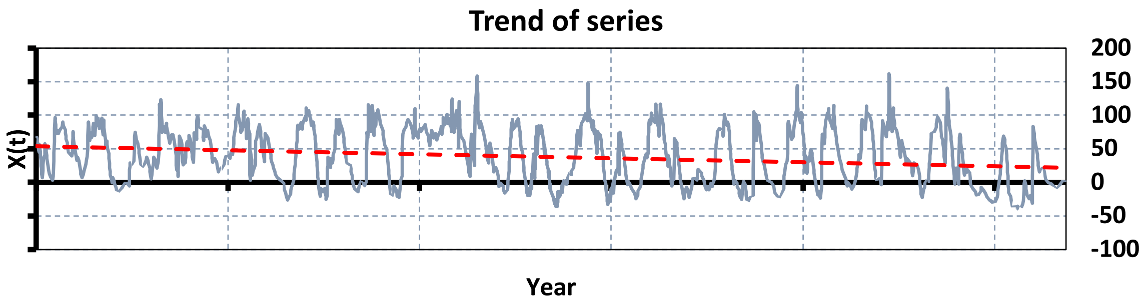


Figure 4.12 *Tendency of the daily hydrometric level plot.*

From the plot of hydrometrical parameters variation, the resulting equation to describe the tendency of the hydrometric level variation during the years was the following:

$$y = -0{,}006x + 290{,}42$$

From the Figure 4.6 was visible a strong variation of the hydrometric values. Then below it has been analyzed more in detail the behavior before 2014 where the hydrometric level oscillations were less strong and after 2015.

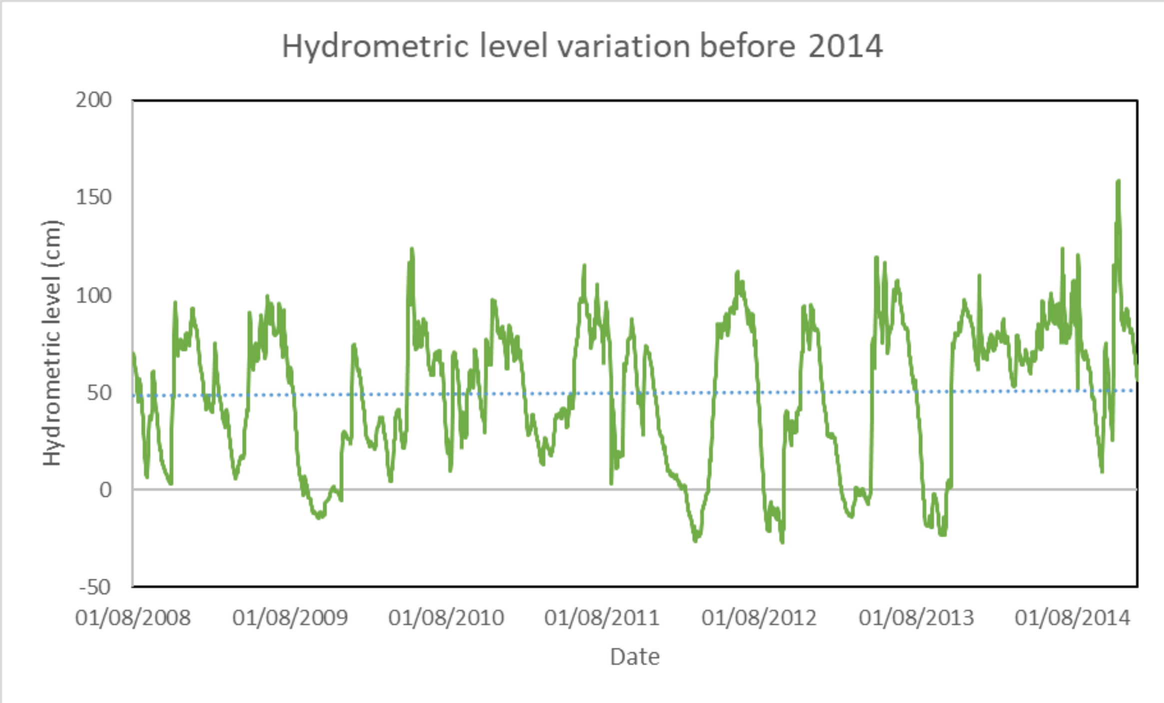


Figure 4.13 *Hydrometric level variation from 2008 to 2014.*

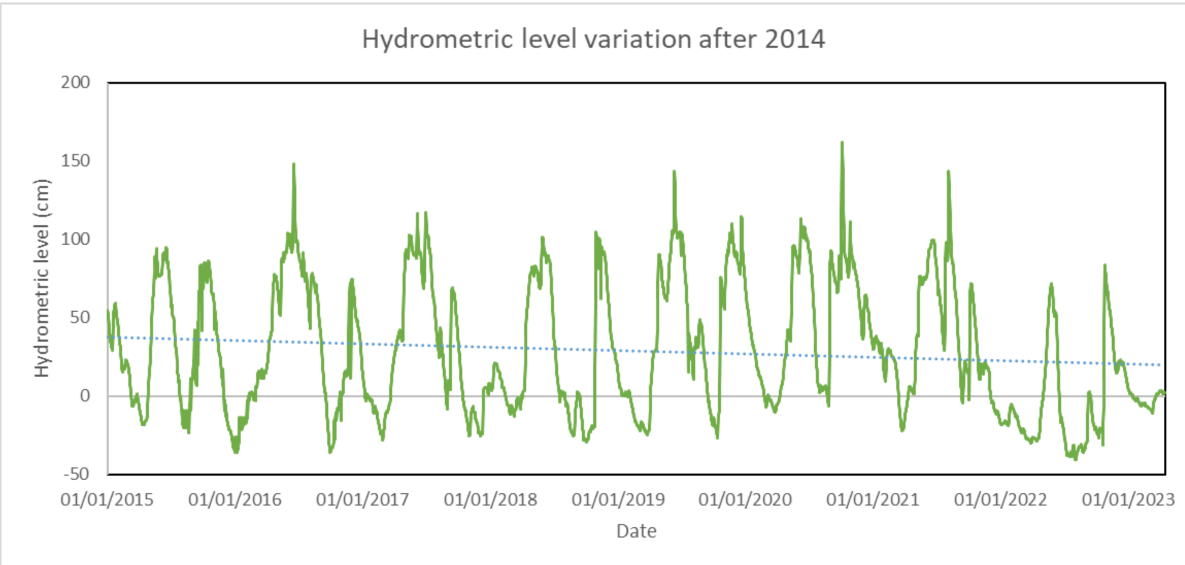


Figure 4.14 *Hydrometric level variation from 2015 to 2023*.

Comparing figures above, Figure 4.14 presents largest variability and extremes, and this is visible from the trend behavior too. In particular, comparing the mean level of both, the second is lower and equal to 28.80 cm with respect to 49.57 cm in the first figure.

4.2.3 Analysis of temperature

In the graph below it has been plotted the mean air temperature of the lake from 2008 to 2023.

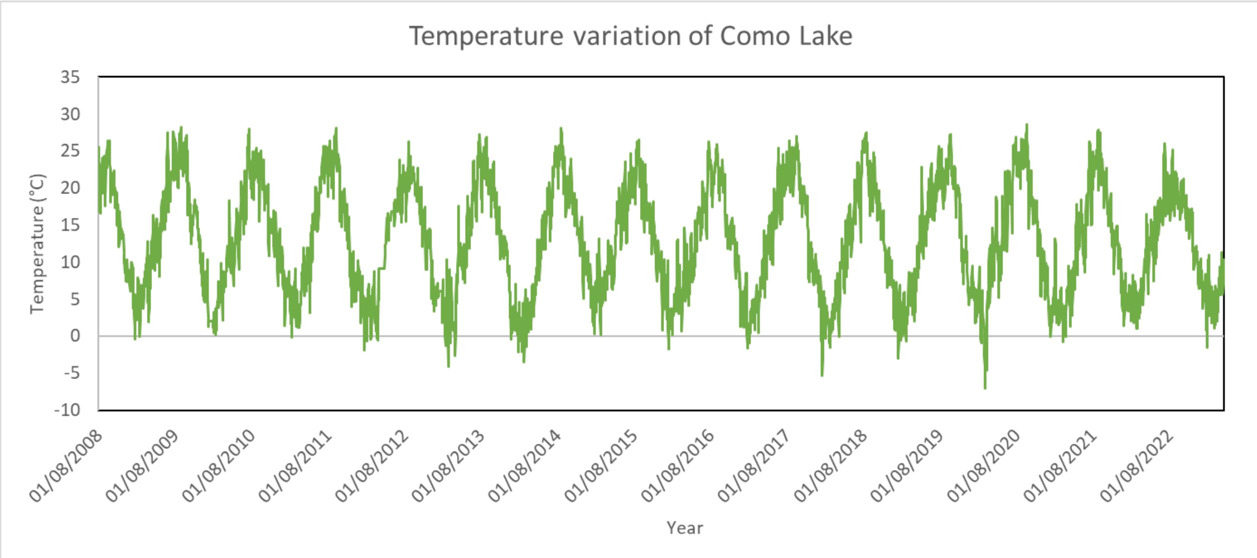


Figure 4.15 *Mean air temperature variation during years.*

From the Figure 4.15 is visible how from 2017 there was an increase of the temperature variation intervals with respect to previous years, but also it is visible how the seasonality component is relevant in this case. The minimum temperature is in 2020 and the maxima too equal respectively to -7 and 29 °C.

Then below it is represented the monthly mean temperature variations in the last 4 years (period of time where larger oscillations are present):

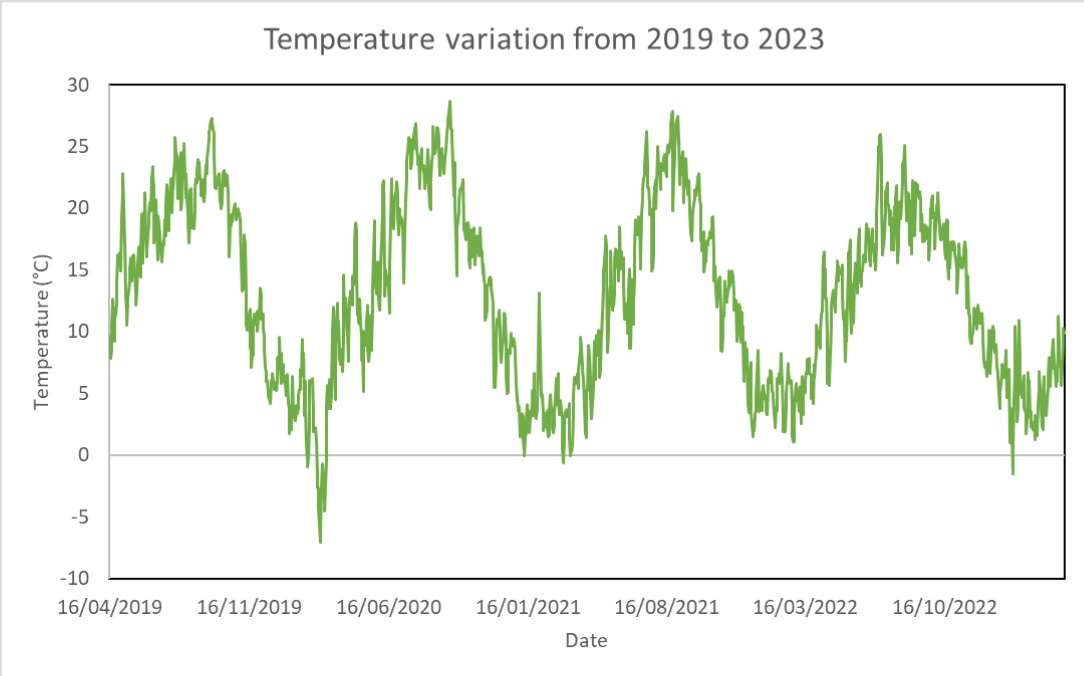


Figure 4.16 *Mean temperature variation from 2019 to 2023.*

Additionally, it has been plotted the mean monthly temperature variations comparing the period from 2008 to 2018 with the trend from 2019 to 2023 where more stronger temperature variations are visible:

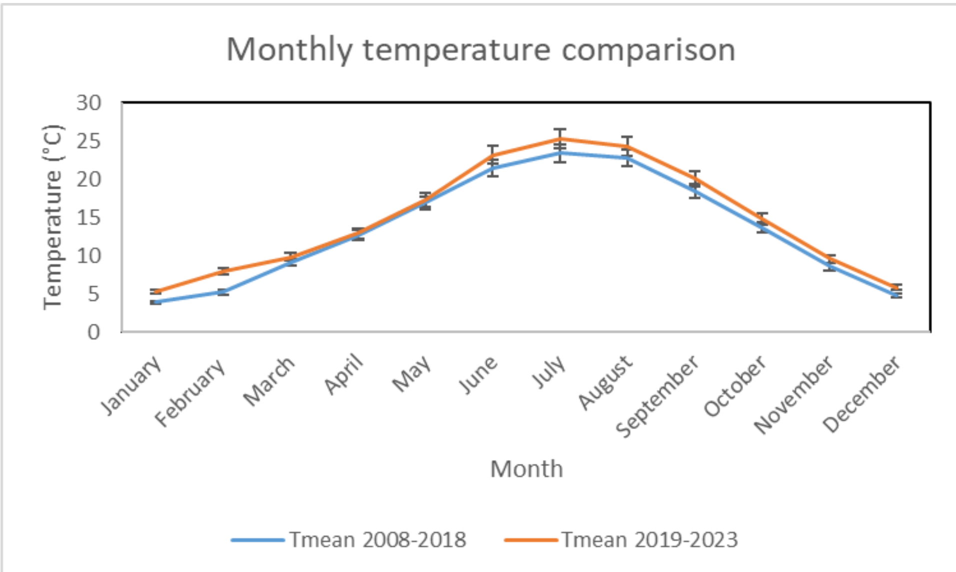


Figure 4.17 *Monthly temperature variation, comparison within different periods.*

The strongest distance within interval of temperatures is visible during winter months (from December to February). This variation is probably due to larger impact of climate change on cold season.

Additionally, it has been considered the monthly temperature variation on the overall period of time comparing the min, max and mean values.

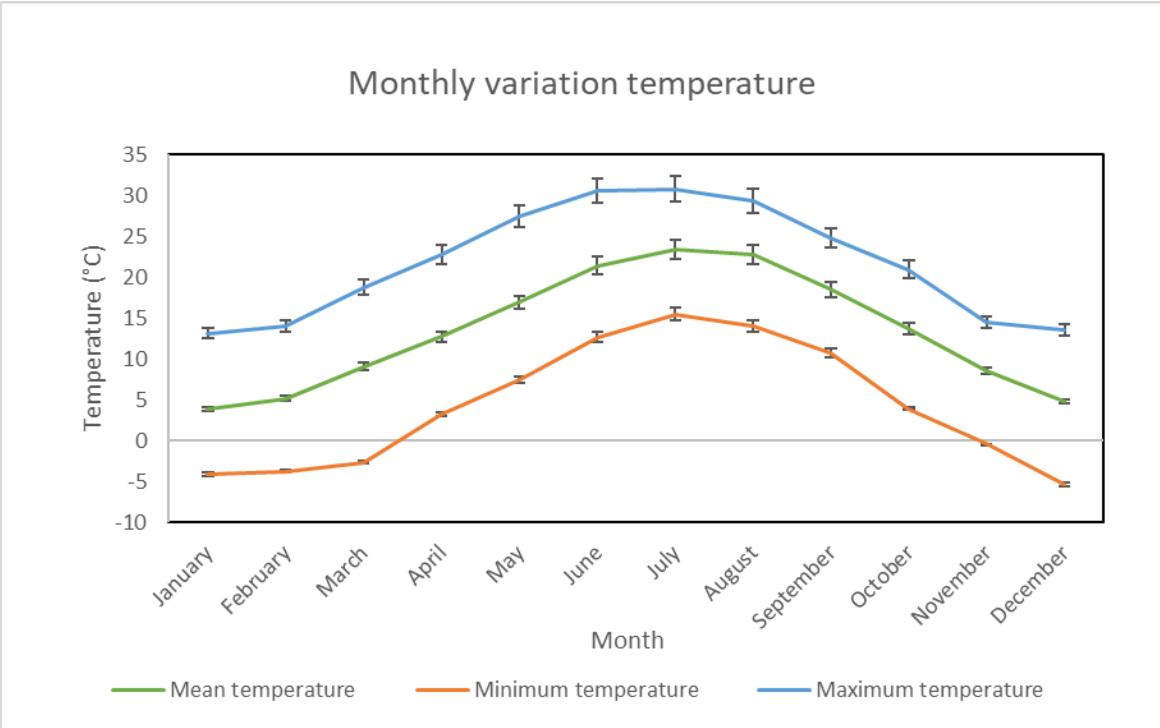


Figure 4.18 *Monthly temperature variation (min, max and mean values).*

Curves behaviors are very similar except for some shift. There is a strong minimum during the winter months with average min temperature below zero value.

4.2.4 Statistics of temperature

From statistical point of view, through the usage of the software ANABASì it was analyzed temperature data series in term of frequency in time.

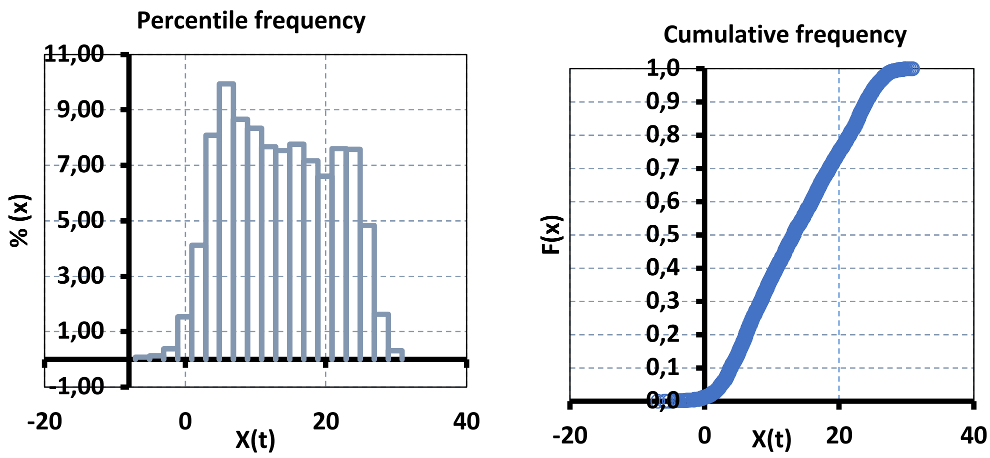


Figure 4.19 *Percentage frequency (left) and cumulative frequency of temperature (right).*

In this case, the data series is characterized by more variability with respect to the case of hydrometric level and percentile frequency. The series follow a Gaussian distribution around the mean value of 13.5.

In the table 4.4 are represented all univariate statistical parameters which are going to describe the series.

Table 4.4 *Statistical analysis characterization results.*

Statistic	Value	Unit of measure
Position index		
Mean	13,51	m
Mode	-	
Minimum (percentile 0%)	-7,08	min
1st quartile (percentile 25%)	7,06	Q1
Median (percentile 50%)	13,13	Q2
3rd quartile (percentile 75%)	19,89	Q3
Maximum (percentile 100%)	30,83	max
Dispersion index		
Inter quartile range (Q3-Q1)	12,82	IQR
Range (max-min)	37,90	R
Standard deviation	7,5	s
Variance	56,5	s2
Variation coefficient	0,6	CV
Shape index		
Asymmetry	0,09	g
Kurtosis	-1,1	k

In the Figure 4.20 it was analyzed the temporal dependency (due to autocorrelation function).

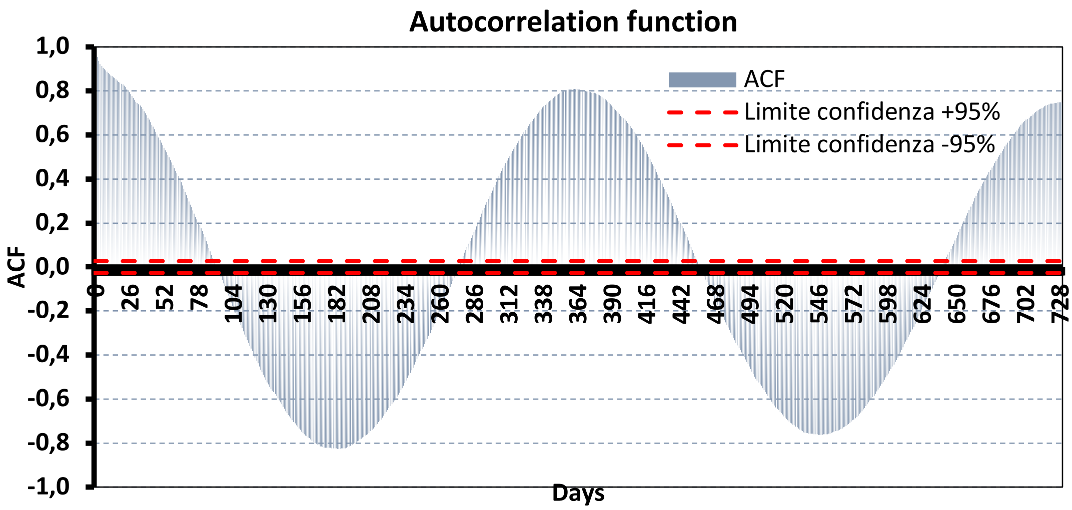


Figure 4.20 *Autocorrelation function for the temperature for 2 years.*

How visible from the above figure, it exists a correlation within data, and it is due to the high seasonality of temperature. Specifically, the value is close to 1 for all period analyzed. Then we could proceed with others statistical analysis to evaluate if present trend, and seasonality and characterize them in a univocal way.

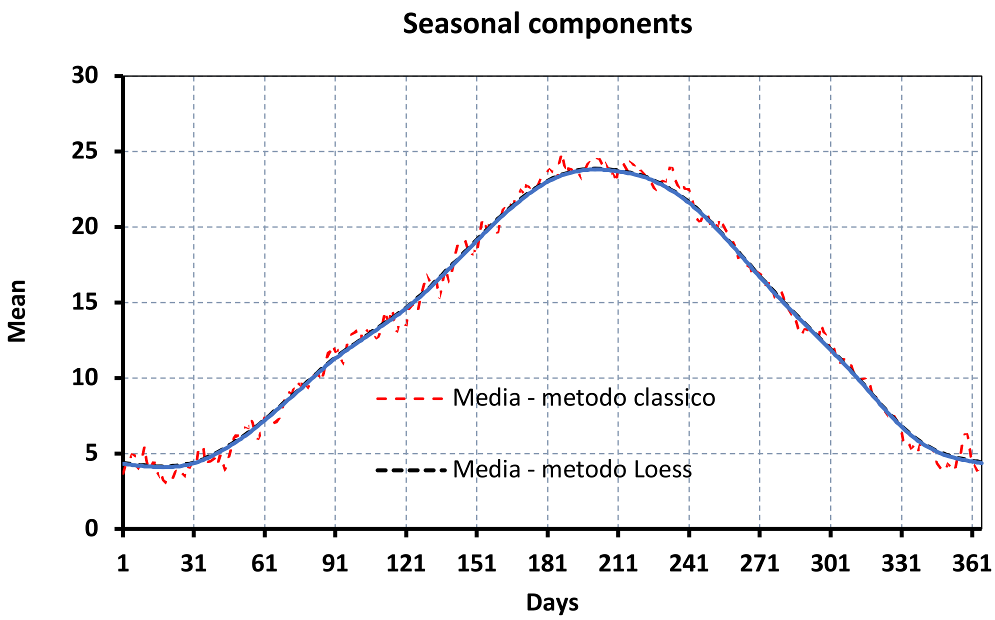


Figure 4.21 *Seasonal components of the mean of the temperature.*

The seasonal variation, with any method used, presents a peak during the summer season as expected for the temperature due to seasonal behavior of temperature. It is possible to see highest values in summer and lowest in January and February.

Then, the presence of a trend in the series was evaluated:

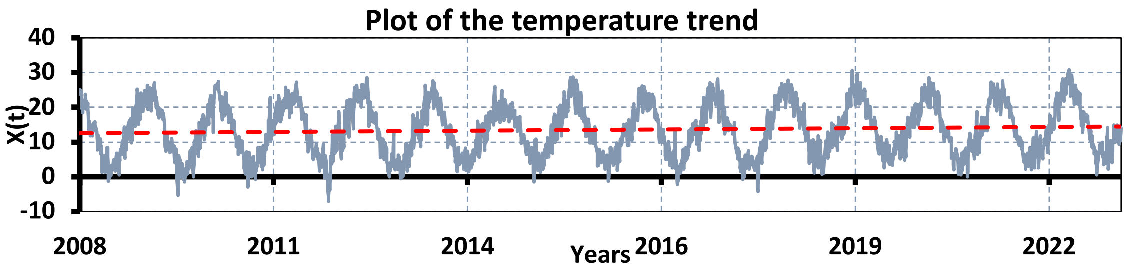


Figure 4.22 *Tendency of the daily temperature plot trend..*

From the plot of temperature trend, the resulting equation that describe the tendency of it is the following:

$$y = 0{,}0004x - 1{,}5967$$

It is visible the presence of a trend into the series and specifically, the trend is around its mean value equal to 12.

4.2.5 Analysis of precipitation

In this paragraph have been plotted precipitation series from different stations for 16 years. In this first part, precipitations were estimated using the arithmetic mean. Later, to get more reliable results, was applied Thiessen method.

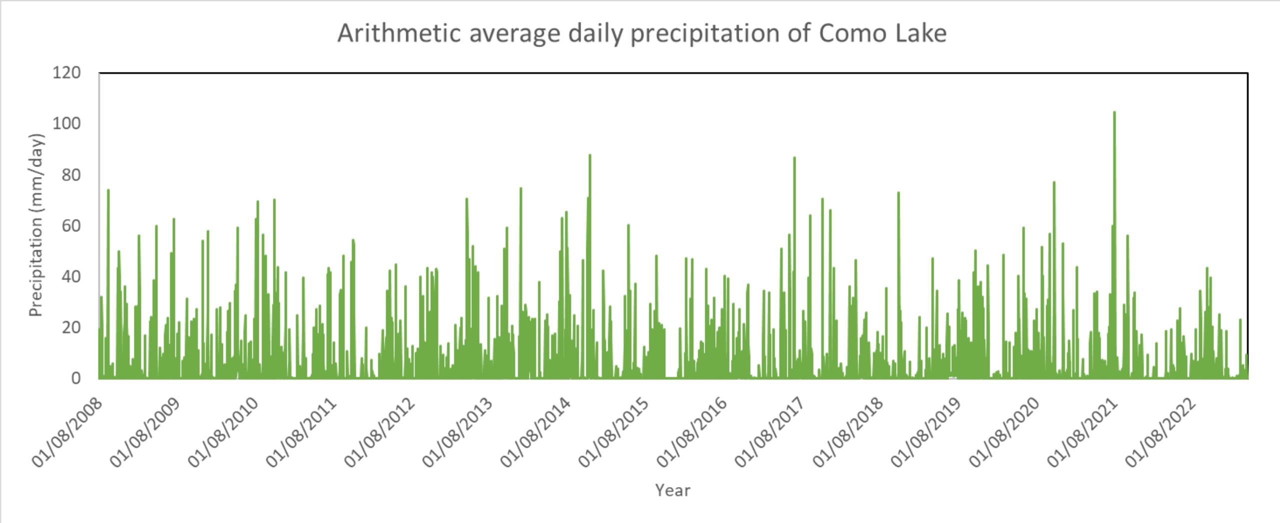


Figure 4.23 *Arithmetic daily precipitation variation.*

Below it has been evaluated precipitations through the application of Thiessen based on areal method. As already discussed in Chapter 3, to get reliable results related to the precipitation, the lake was subdivided into areas using GIS software. Specifically, the watershed considered was subdivided into areas with at least one station on it and all zones were characterized by similar values of area.

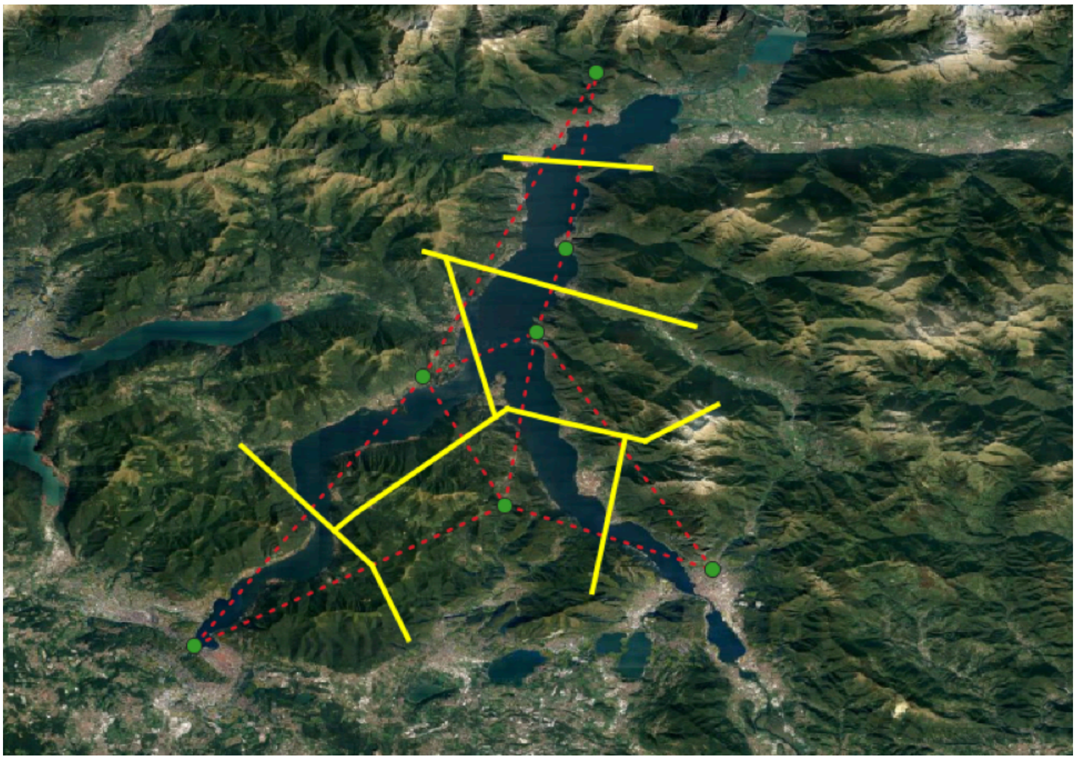


Figure 4.24 *Thiessen method application on Como Lake.*

Using Thiessen method, it has been plotted the precipitations for 16 years:

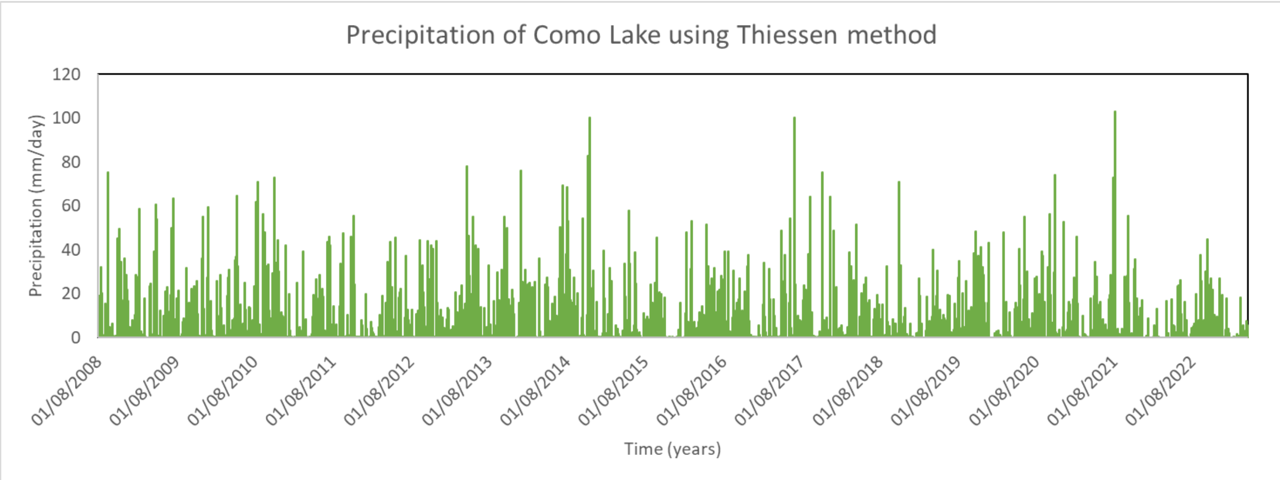


Figure 4.25 *Daily precipitation variation using Thiessen method.*

Additionally, it was also estimated the annual cumulative precipitation along all years considered.

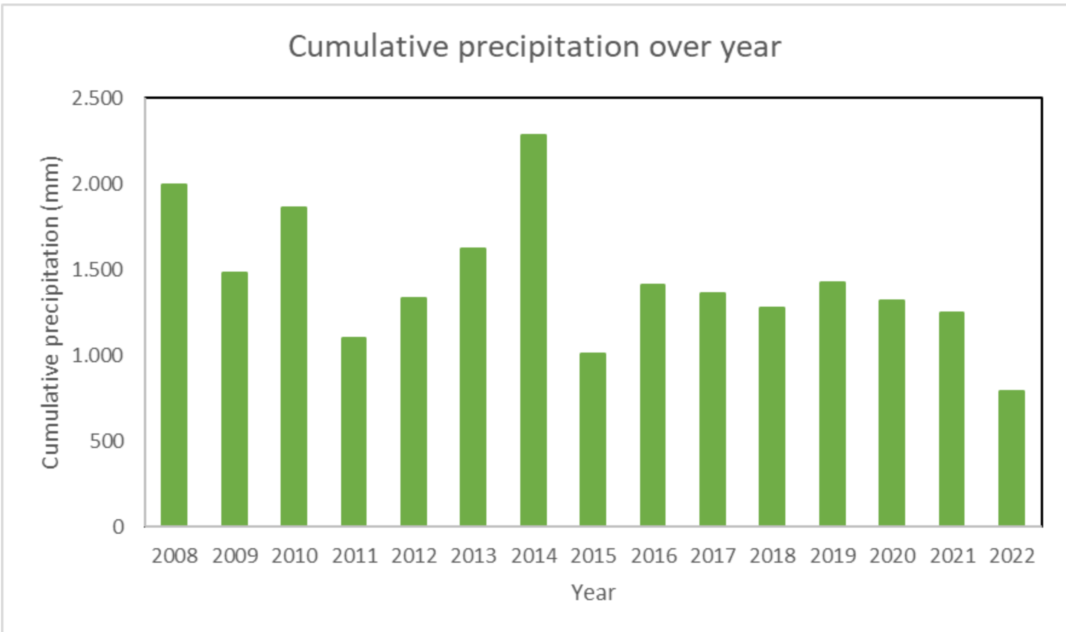


Figure 4.26 *Cumulative year precipitation using Thiessen method.*

From Figure 4.26 it is visible how in the years from 2008 to 2015 there is strong variability of precipitation and much more in term of overall precipitation with respect with the latest years. This decreasing amount is probably due to the climate change action which produce more stronger event but overall, less amount of precipitation.

4.2.6 Statistics of precipitation

Precipitation is one of the main parameters used in hydrology to get information about the water basin. To make a rough evaluation, arithmetic average has been calculated, but this methodology in the precipitation field is characterized by a lot of limitations: it doesn't consider the day in which there is no precipitation, and it does not consider the spatial variability of rain. To overcome this limitation, average precipitations have been plotted using the Thiessen method. Anyway, even this last method used presents limitations, the best approach to evaluate this parameter is to use models.

A statistical analysis has been performed in this paragraph.

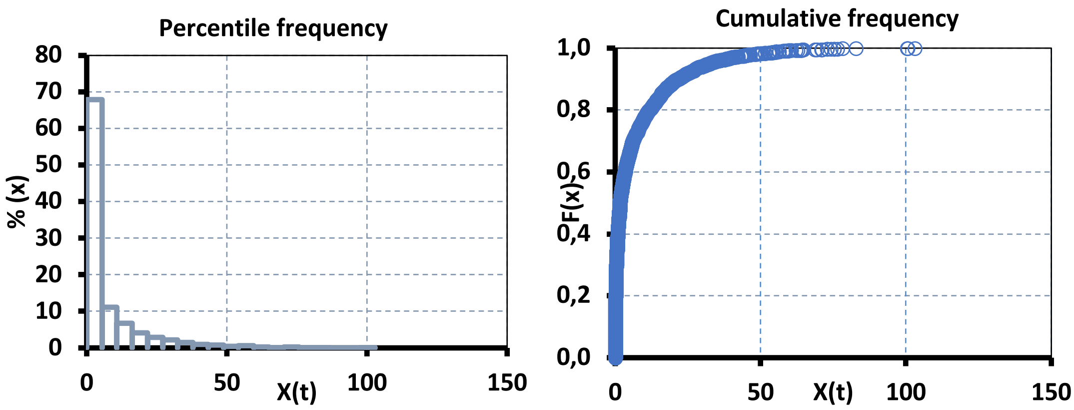


Figure 4.27 *Percentage frequency (left) and cumulative frequency of precipitation (right).*

From the Figure 4.27 are visible the distribution of precipitation which is almost all around 5 mm.

In the Table 4.5 are represented all the univariate statistical parameters which are going to describe the precipitation series.

Table 4.5 *Statistical analysis characterization results.*

Statistic	Value	Index
Position index		
Mean	7,08	m
Mode	-	
Minimum (percentile 0%)	0,01	min
1st quartile (percentile 25%)	0,21	Q1
Median (percentile 50%)	1,60	Q2
3rd quartile (percentile 75%)	8,48	Q3
Maximum (percentile 100%)	102,90	max
Dispersion index		
Inter quartile range (Q3-Q1)	8,27	IQR
Range (max-min)	102,90	R
Standard deviation	12,1	s
Variance	146,1	s2
Variation coefficient	1,7	CV
Shape index		
Asymmetry	2,90	g
Kurtosis	10,7	k

From the Table 4.5 is possible to understand how values are totally positive asymmetric due to the value of asymmetry higher than 0 and positive.

Through hydrological statistical analysis was extracted the temporal linear dependency (due to autocorrelation function) within data.

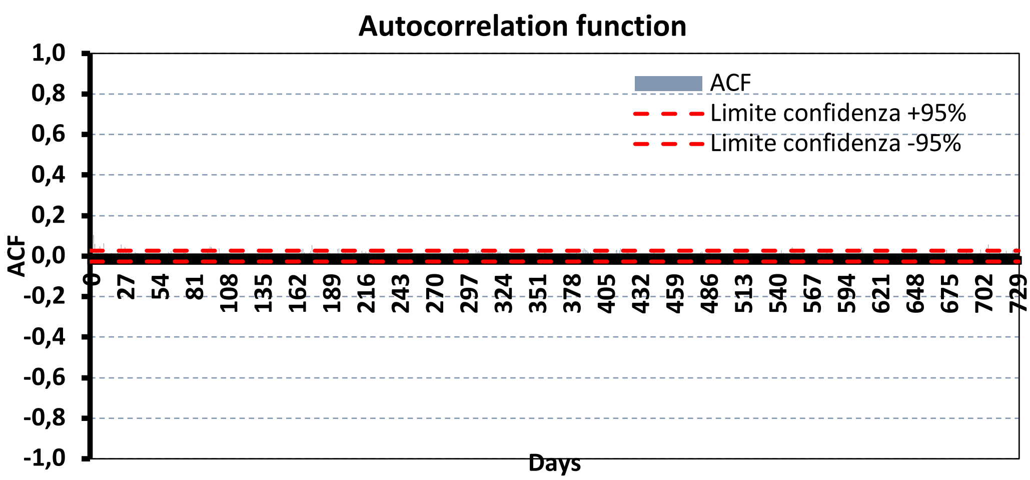


Figure 4.28 *Autocorrelation function for the precipitation along 2 years.*

From the autocorrelation test result, it is visible how there is not any correlation within series. Specifically, there is not any homogeneity of the data. As a consequence, it was not performed additional analysis not being temporal and spatial variability of precipitation statistically significative (Majid Javari, 2016).

4.2.7 Analysis of evapotranspiration

From the knowledge of the mean temperature and solar radiations (*Ra*), it was possible to estimate through the empirical (temperature based) method of Hargreveas, the potential evapotranspiration in the watersheds. Despite this method gives values of reference crop evapotranspiration, anyway it is representative expression for potential evapotranspiration (Matteo Gentilucci et all., 2021).

Values of *Ra* have been found through daily calculation in according with values of latitude, inclination of Earth and hour angle of the lake. The extracted data from database were in W/m^2 which was transformed into mm/d to be used in the calculation.

This formulation was not used for the lake because only the evaporation component is present. In the last case, the Penman formulation has been used.

The average ETP variation is represented in the Figure 4.29 below.

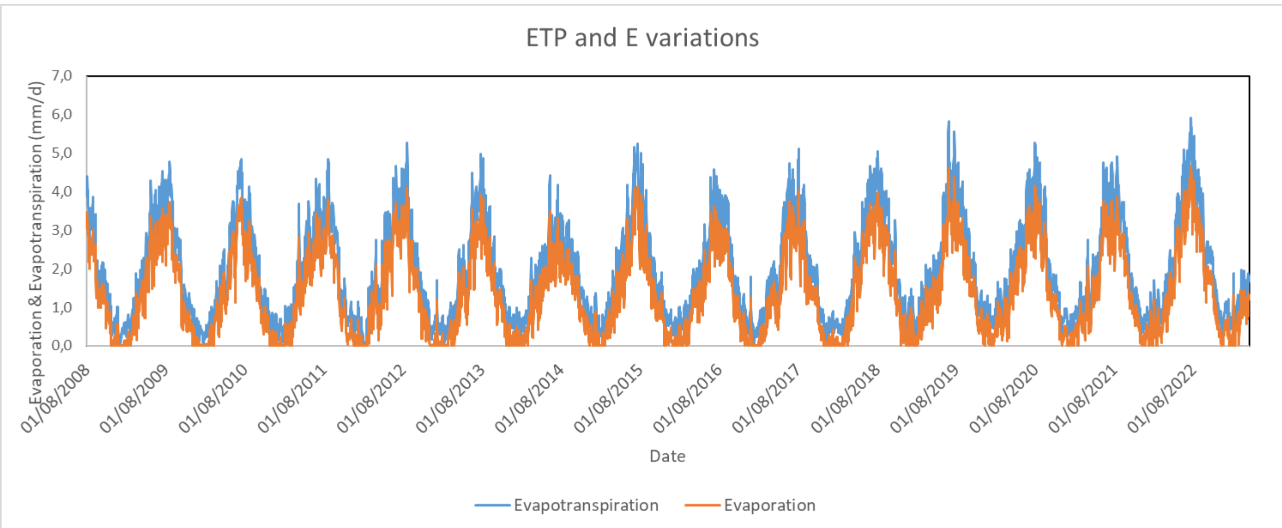


Figure 4.29 *Evaporation and Evapotranspiration variation.*

From the Figure above is visible how the behavior of evaporation is very close to the ETP, this because the transpiration phenomenon is less strong and highly influenced by temperature. Then we got values close to zero for both evaporation and transpiration during the winter period. Transpiration being performed by plants is almost constant along all year, and it is going to produce a shift of the ETP with respect to the mean value of evaporation.

The evapotranspiration values have been calculated from different points of the watershed to take into account the variation of the altitude and then the temperature variations.

In the Figure 4.30 mean monthly cumulative components of ETP are represent:

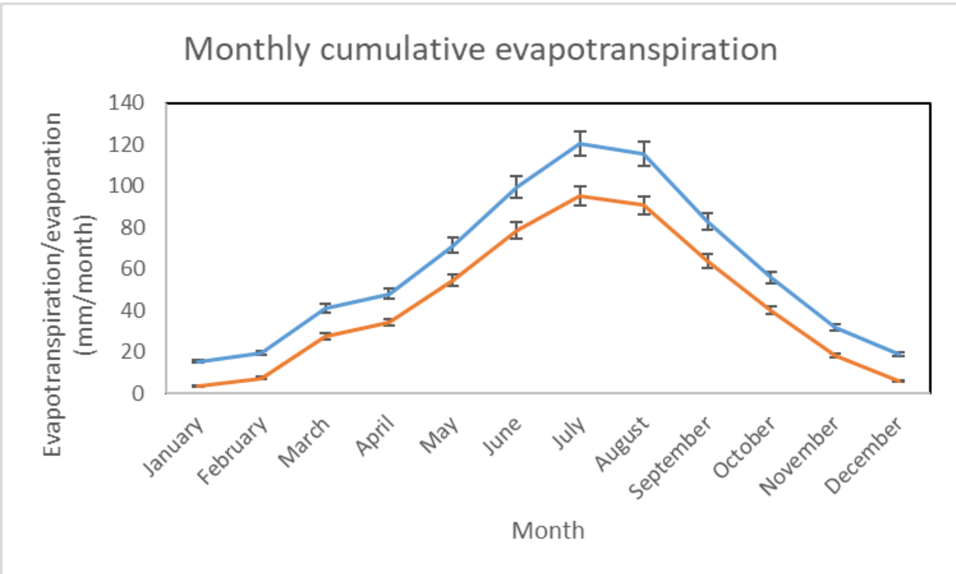


Figure 4.30 *Mean cumulative monthly values of ETP.*

Similarly, to already seen, the evaporation component during months with higher temperature is larger both for basin and lake. The transpiration component is anyway important because a large amount of plant is present around the lake and only a small portion of mountains during winter months present the snow (Jamei Li et all., 2023).

4.2.8 Analysis of discharge

Discharge is defined as the amount of water which pass through a section within the time t. Generally, this parameter is estimated because very complex to measure. The hydrological balance usually is good methodology to get approximation of this parameter. Alternatively, despite more complex to estimate, the stage-discharge curve could be constructed. In our case, for inflows and outflow, stage-discharge curves have been used gave by ARPA:

INLET RIVER

- Adda $q_{in\text{-}Adda}=51{,}57(h+0{,}431)^{2{,}756}$
- Mera $q_{in\text{-}Mera}=0{,}899(h+0{,}841)^{5{,}31}$

OTLET RIVER

- Adda $q_{out}=0{,}311(h+100)^{1{,}637}$

Where h is the hydrometric level (m) and q is the discharge (m^3/s).

The hydrometric level values, extracted from ARPA, have been reported to the same altimetric level before to be transformed into discharges.

The series of data extracted was complete along all years only for the outflow (from 2008 to 2023) while for the inlet rivers were only partial. This is the reason why for the inlet rivers after calibration, the HBV model has been used to estimate the overall discharge.

To evaluate discharges series of the inflows firstly it has been defined basins and then in them it was evaluated precipitations, ETP and temperature variations.

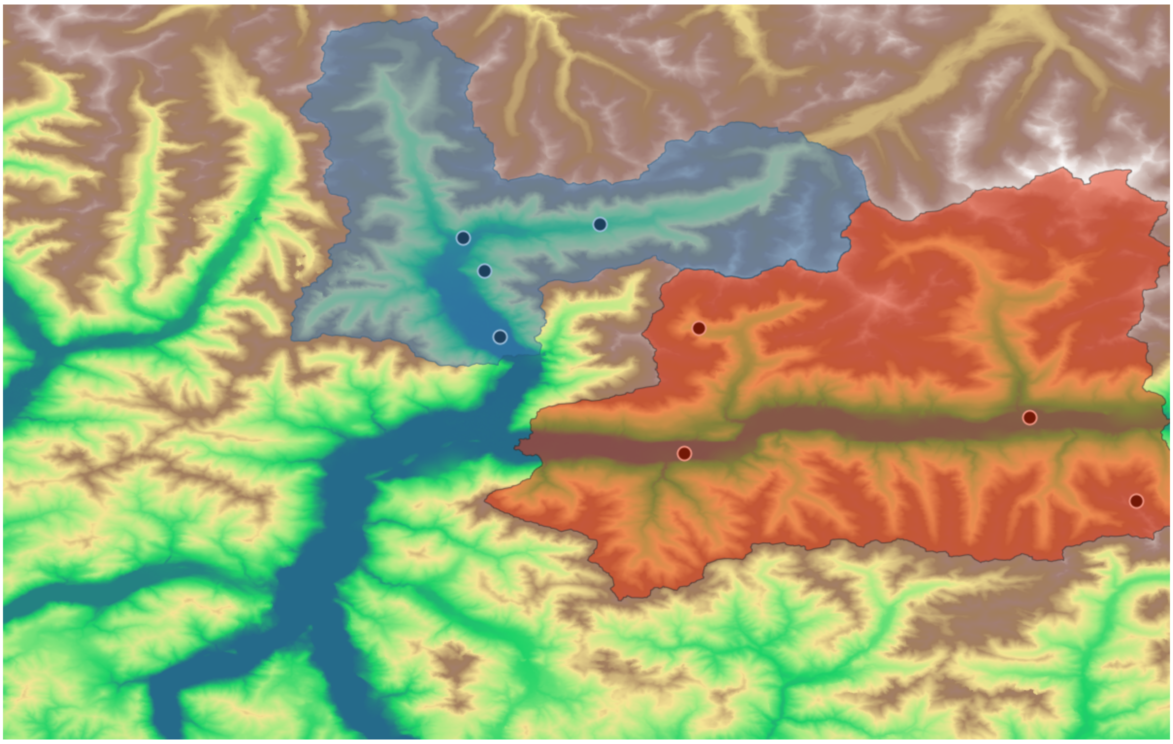


Figure 4.31 *Adda (red one) and Mera watersheds (blue one) and their measurement stations.*

Specifically, in the Figure 4.31 is represented the area of watersheds in which the inlet rivers are present. From measurements stations present into the DEM, precipitation, ETP and temperature have been extracted. These parameters and the discharges estimated through the stage-discharge curves were necessary to run the model.

Figures 4.32 and 4.33 are represented the hydrometric level in the Adda and Mera basins used to estimate the discharges.

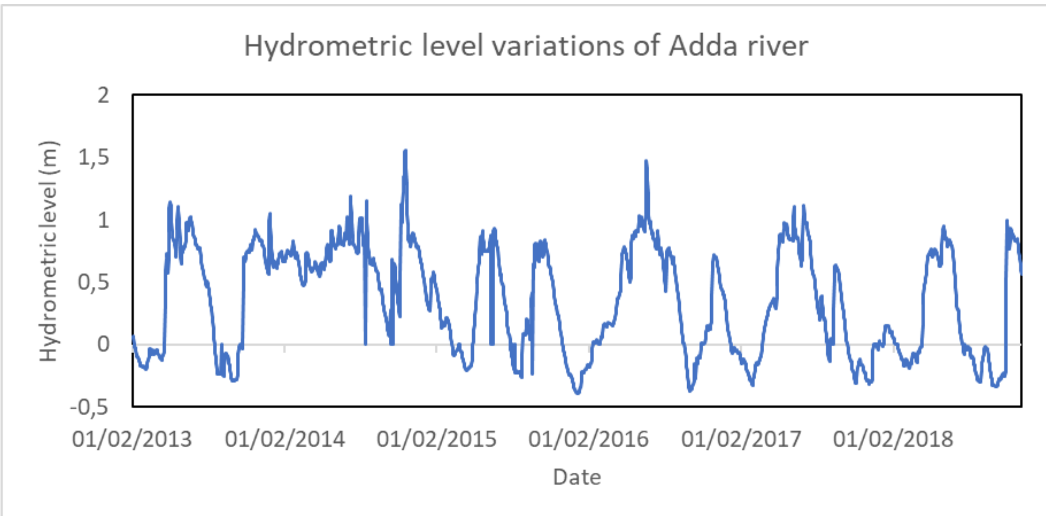


Figure 4.32 *Adda hydrometric level.*

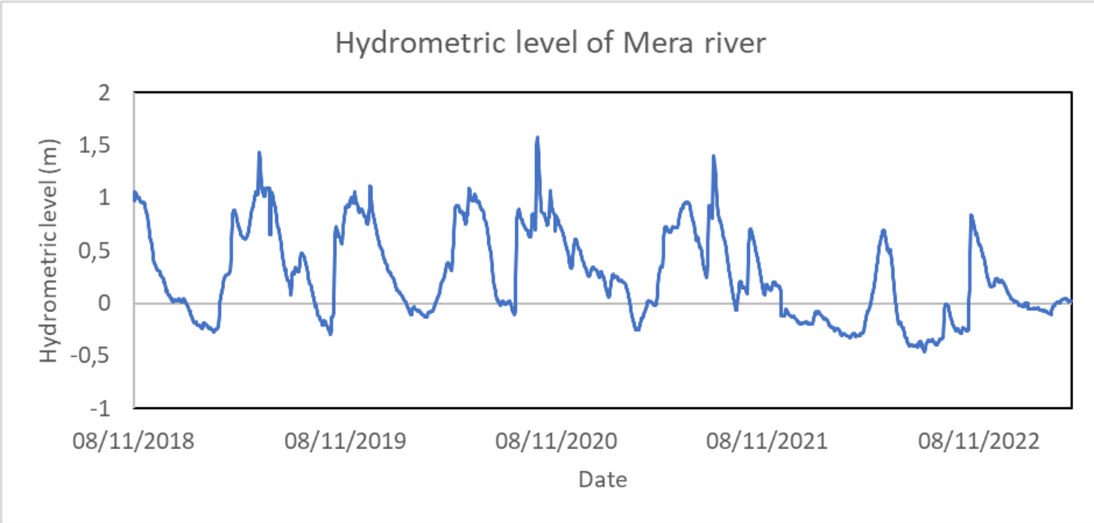


Figure 4.33 *Mera hydrometric level.*

Despite from the Figures 4.32 and 4.33 seems the same values of discharges, anyway the discharges differ one order of magnitude. The correction is included in the stage-discharge relationship used.

Then, in the figure below, it has been estimated the discharge values using the stage-discharge curves given by ARPA for all basins:

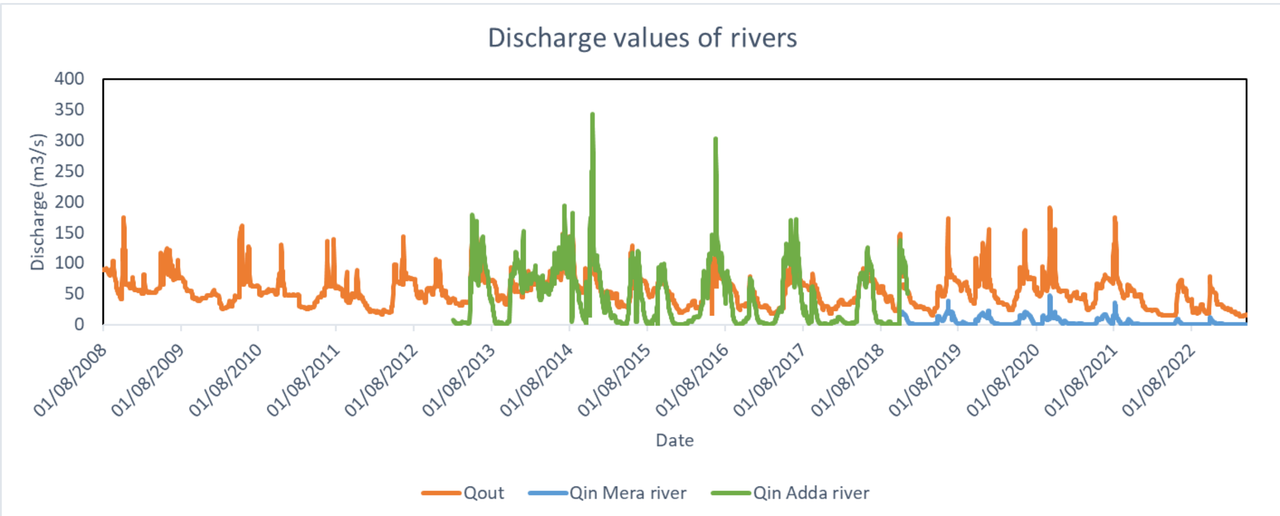


Figure 4.34 *Discharge values of all 3 basins.*

It is visible from Figure 4.34 how the inflow from Adda has the larger discharge values. For the inflows the data are partial while for outflow the series of data is complete.

4.3 HBV model

The series of inflows data, not being enough long in time, were elaborated using HBV software to forecast the missing data.

HBV is a conceptual model which require as input only few parameters as precipitation, temperature and ETP for any series that could be analyzed. Specifically, it is requested areal precipitation that have been calculated through the Thiessen method and ETP estimated using the method of Hargreveas and then corrected with the formulation defined into Materials and methods (Chapter 3).

The main output from the model was a comparison between simulated daily discharge and calculated in which the last are estimated for all temporal series.

The calibration was performed using trial-and-error method with the aim to reduce as much as possible the volume error combined with the value of R^2 (Gorah Lindstrom, 1997).

The analysis was performed subdividing the overall area into basins. All parameters used in the HBV simulation were referred to the total basins.

To apply the model and then estimate the discharge, additional parameters of this zone were extracted from measurement stations visible as points in the Figure 4.31. Due to the presence of mountains, in these 2 basins, a correction of parameters, function of altitude, were performed.

Precipitations were extracted and through the Thiessen method elaborated:

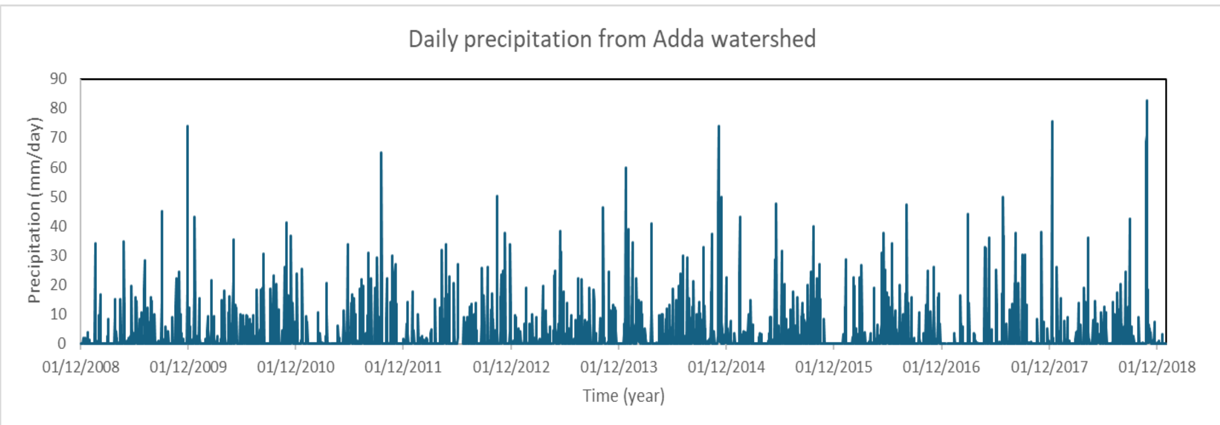


Figure 4.35 *Precipitation variation in Adda watershed.*

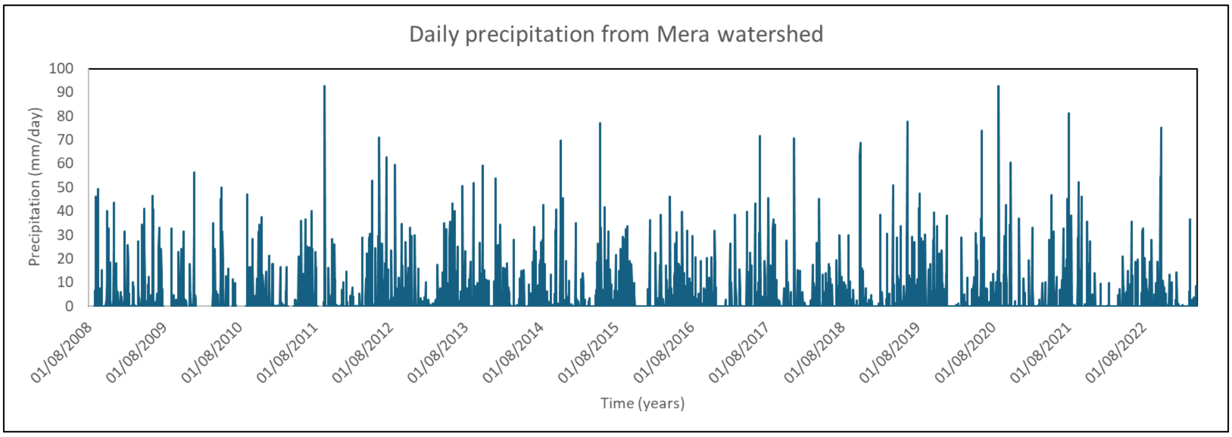


Figure 4.36 *Precipitation in Mera watershed.*

The run of model was performed searching for the objective function R_{eff} the value of 1 and the model was run 5000 times. The choice of parameters used and represented in the Table 4.6 are the one which maximize the value of R_{eff} with the goal to find the best performances. In this way the calibration phase has been performed.

From the calibration the parameters get are represented in the Table 4.6.

Table 4.6 *Parameters from calibration of standard model.*

Parameter	Symbol	Adda's value	Mera's value	Unit
Threshold temperature	TT	0.87	0.89	°C
Degree-day factor	CFCMAX	3.89	3.57	mm/°C d
Snowfall correction factor	SFCF	1.05	1	-
Refreezing coefficient	CFR	0.05	0.05	-
Water holding capacity	CWH	0.1	0.1	-
Maximum of soil moisture zone	FC	100	110	mm
Threshold for evaporation reduction	LP	0.8	0.75	-
Shape coefficient	Beta	1	1.4	-
Recession coefficient (upper stor.)	K0	0.1	0.2	1/d
Recession coefficient (upper stor.)	K1	0.04	0.01	1/d
Recession coefficient (lower stor.)	K2	0.01	0.01	1/d
Threshold for K0 to become K1	UZL	35	30	mm
Maximum percolation	PERC	1.67	1.24	mm/d

Routing parameter	MAXBAS	1.3	1	d
Correction factor for potential evapotranspiration	CET	0.3	0.1	1/°C

In Figures 4.37 and 4.38 there are the results get from the run of model, respectively for Adda and Mera rivers, using the above calibrated parameters assuming standard model.

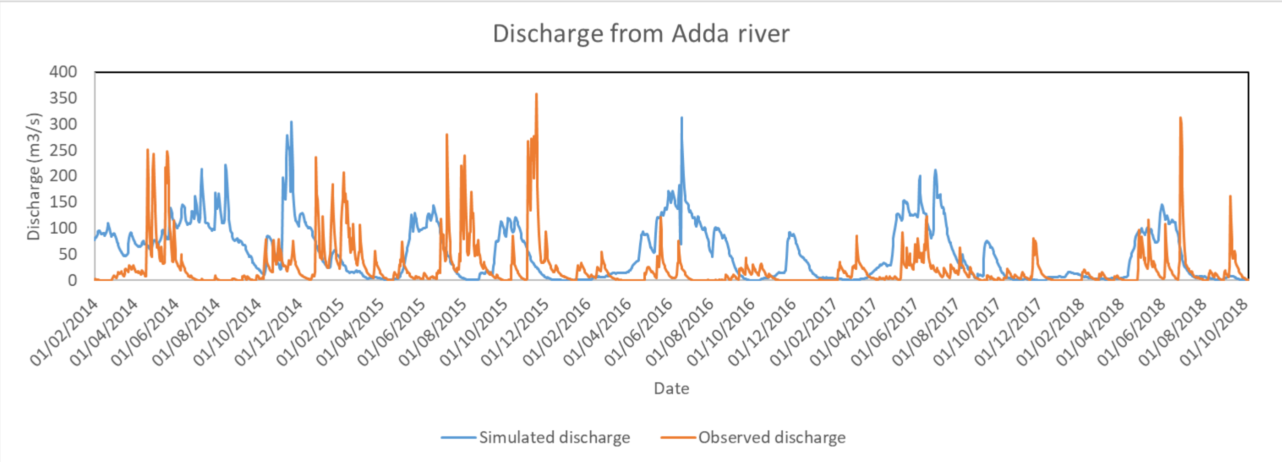


Figure 4.37 *Discharge results from standard model application for Adda river.*

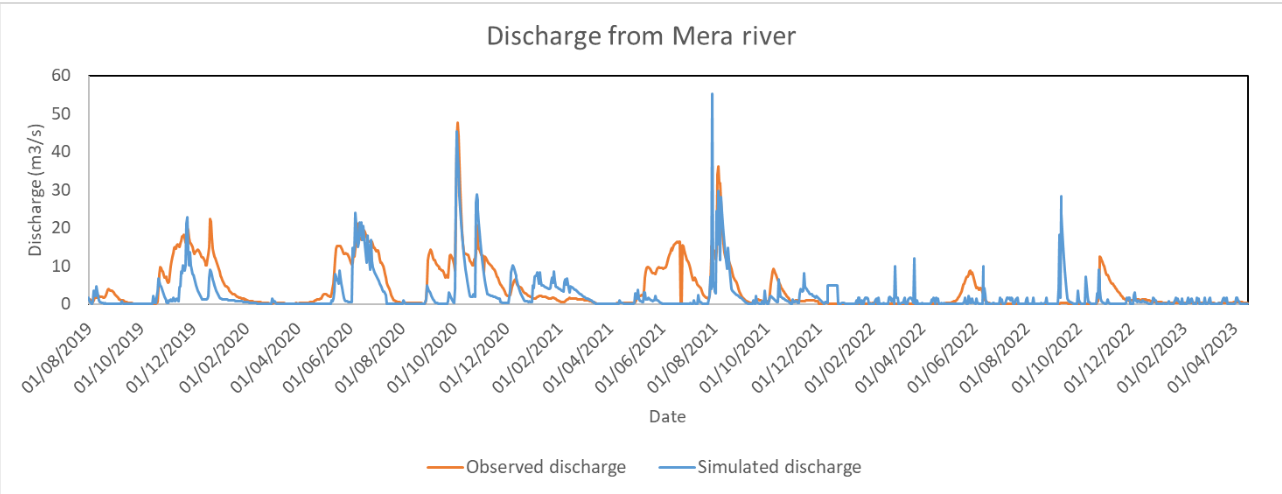


Figure 4.38 *Discharge results from standard model application for Mera river.*

A deviation between the observed and simulated discharge is present. Some bias present in the observed discharge could be due to approximation used in the stage-discharge method or in the approximation made in the software. In fact, within the assumption made in the software there are the validity of standard model and the parameters defined into the characterization of watersheds.

In the Figure 4.37 looks like the software found precipitations that were not. Additionally, being a zone close within mountains, the snow component into the model has been considered and it is visible from the behavior of peaks which are going to decrease requiring more time than precipitation.

Visually we have that Adda produces the largest inflow into the lake with a peak of 300 m^3/s, far from Mera river which maximum values are around 40 m^3/s. For what concern the mean values, for Mera they are around 6 m^3/s, while for Adda 70 m^3/s, almost one order of magnitude of difference.

Despite the historical data series were short, anyway, all series except the first year for both rivers were used to make calibration. The first year of both series was used to make validation of the series. The validation of series has been plotted and represented in the Figure below and it is based on the data given by the application of model. The limitation of this model was the possibility to use only one year for the validation.

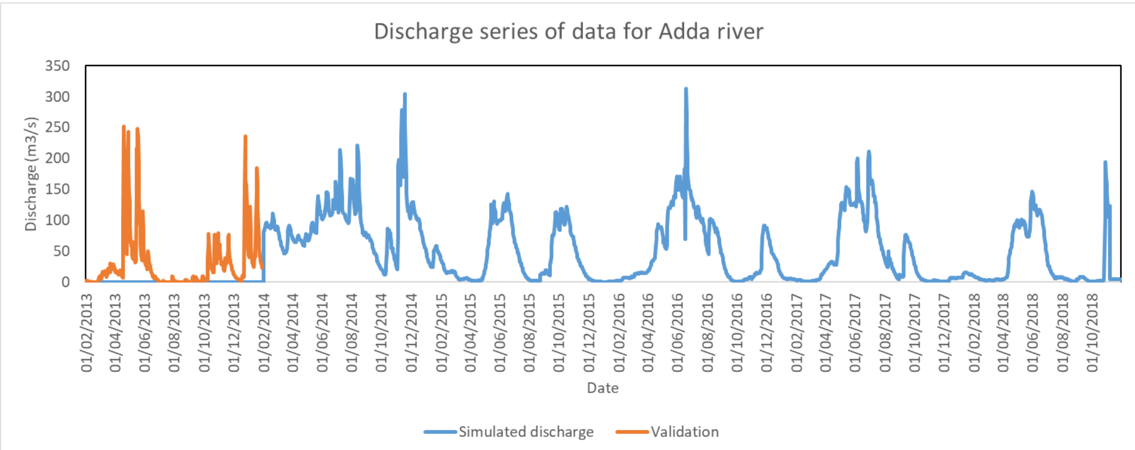


Figure 4.39 *Validation of estimated discharge for Adda basin.*

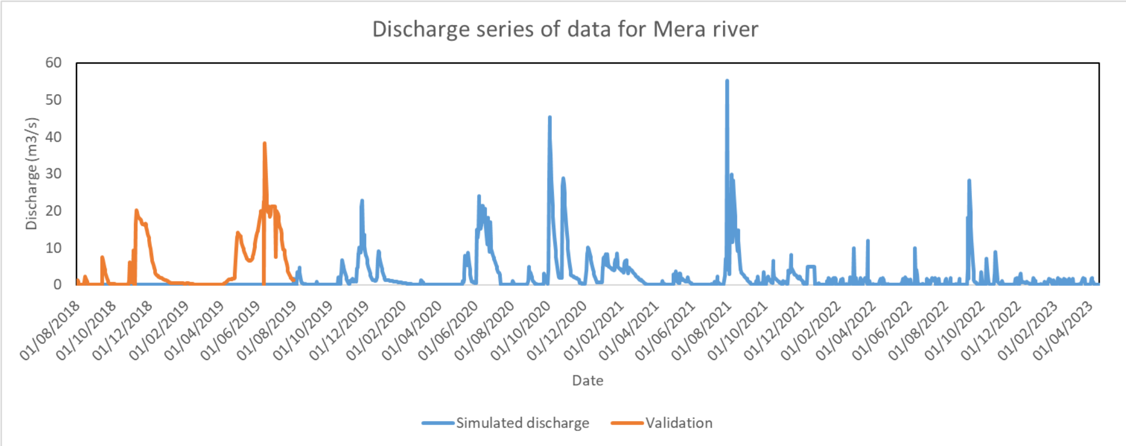


Figure 4.40 *Validation of estimated discharge for Mera basin.*

In these chapter it is then represented the results get from model application for the inflows into Como lake estimation. The adherence within measured and simulated series have been evaluated using 2 statistical parameters: *Reff* and KGE.

Table 4.7 *Comparison between statistical parameters from model application..*

Data series	*Reff* (calibrated)	KGE (calibrated)	*Reff* (validated)	KGE (validated)
Adda river	0,84	0,77	0,75	0,59
Mera river	0,79	0,72	0,73	0,67

From the Table 4.7 it looks that the model despite not so close to the real condition of rivers, anyway, represents the condition that we searched. Since the validation and calibration have been performed with the same indices, the validation values are lower than the calibrated, this is due to the lowest amount of data available, and the data used based on calibration.

Additionally, the cumulative level of discharges, observed and simulated, have been plotted to evaluate cumulative monthly (rectangles) and cumulative annual values (lines) for both rivers.

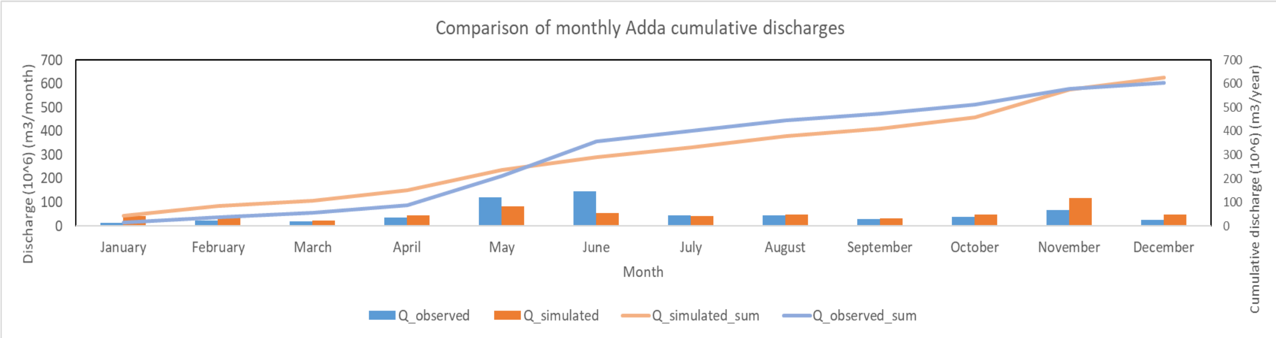


Figure 4.41 *Comparison of cumulative monthly and annual value of discharges for Adda basin.*

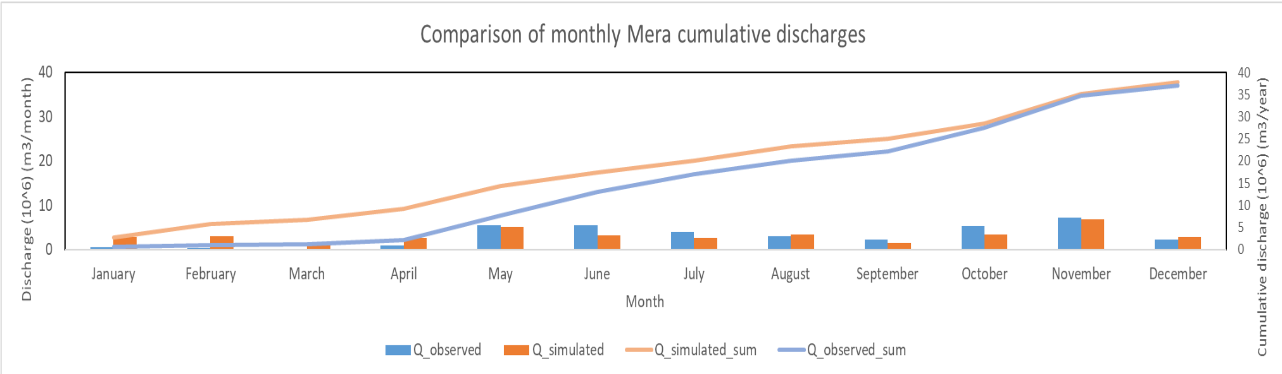


Figure 4.42 *Comparison of cumulative monthly and annual value of discharges for Mera basin.*

Table 4.8 *Percentages of variation within simulated and observed monthly discharges for both rivers.*

Months	January	February	March	April	May	June	July	August	September	October	November	December
Mera river	62,72	69,81	69,32	62,75	30,49	14,43	8,18	7,69	5,81	1,54	0,46	1,07
Adda river	49,42	39,06	32,05	26,29	5,77	-10,38	-9,61	-7,95	-7,28	-5,69	-0,19	1,69

It is visible how for both rivers, despite the monthly cumulative values of discharge differ within the observed and the simulated one, anyway the overall annual volume is very similar within observed and simulated. This means that the overall simulation is performed well despite there are some delays in the water discharge or underestimation. Specifically, looking at the difference within the cumulative values for what concern Mera river, the initial difference percentage within values goes from values around 70% till be reduced to 1% at the end of the year. How it is visible from the Figure 4.42 and confirmed by the percentages, it looks like that there a very slow release of water. This is probably due to the presence of infiltration in the soil that it is simulated by the software as a snow.

For what concern Adda river, despite during the 4 initial months we have similar situation, after that the observed discharges become larger with respect to the simulated. Specifically, it is important to take into account the presence of some hydropower plants along Adda river that are modelled by the software as accumulation. In this way it is explained mostly the presence of water release with delay.

Comparing Figure 4.41 and 4.42, it is visible how in the case of Adda the volume difference within observed and simulated curves is much smaller with respect the case of Mera because the presence of artificial basins modified the hydrometric regime but not the volumes. The small difference anyway present, could be due to infiltration or ETP variation.

4.4 Hydrological balance

Using the hydrological balance as defined into paragraph 3.2.6 were possible to find the groundwater term and the error associated to the model. Specifically, the hydrological balance represents the amount of water which daily is present into the lake, and it is function of the variation of a lot meteo-hydrological parameters.

In this last part related to the balance, any calculation is referred to the Como lake basin.

In the balance estimation the channels present as inflows and outflow have been neglected and were not considered.

Firstly, it has been plotted in the Figure 4.43 some water contributes (precipitation, evapotranspiration and evaporation) defined in term of water height.

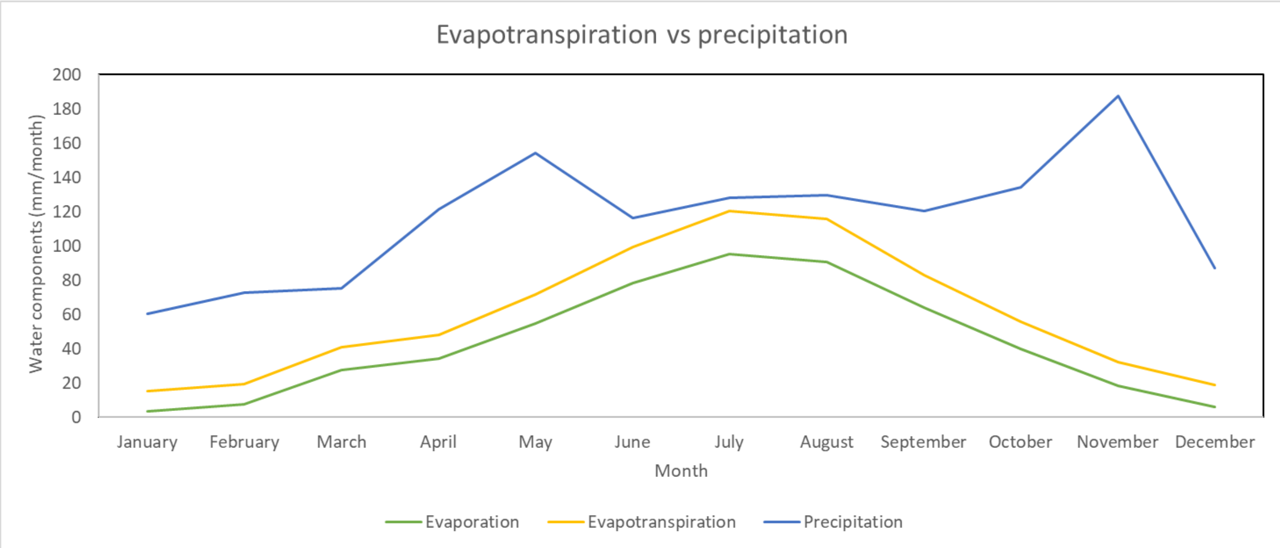


Figure 4.43 *Monthly water component plot.*

It is visible how the place is a humid zone due to larger precipitation components with respect to the evaporation and evapotranspiration.

At this point, before the estimation of hydrological balance that it is going to permits the estimation of the groundwater component, due to the water exchange within the lake and the groundwater, it has been estimated the change in storage component.

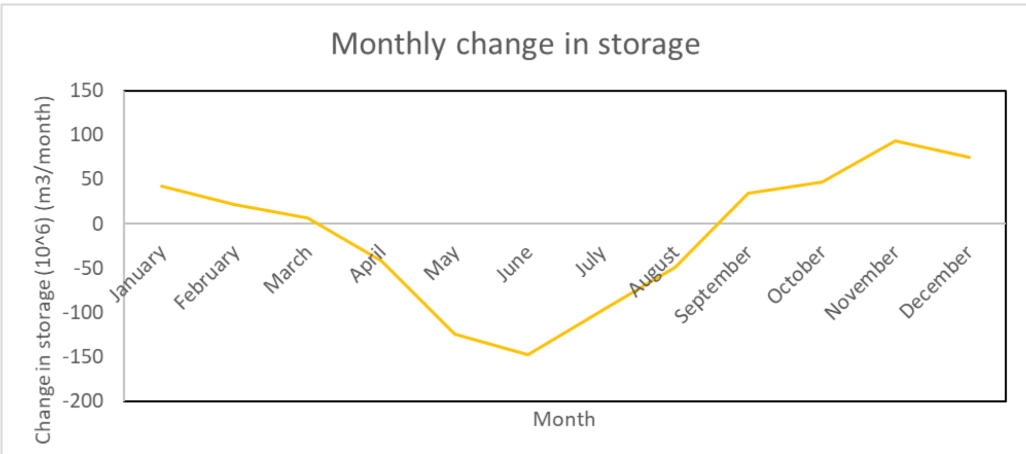


Figure 4.44 *Monthly change in storage.*

The variation and relationship within volume water parameters have been represented in the Figure 4.45.

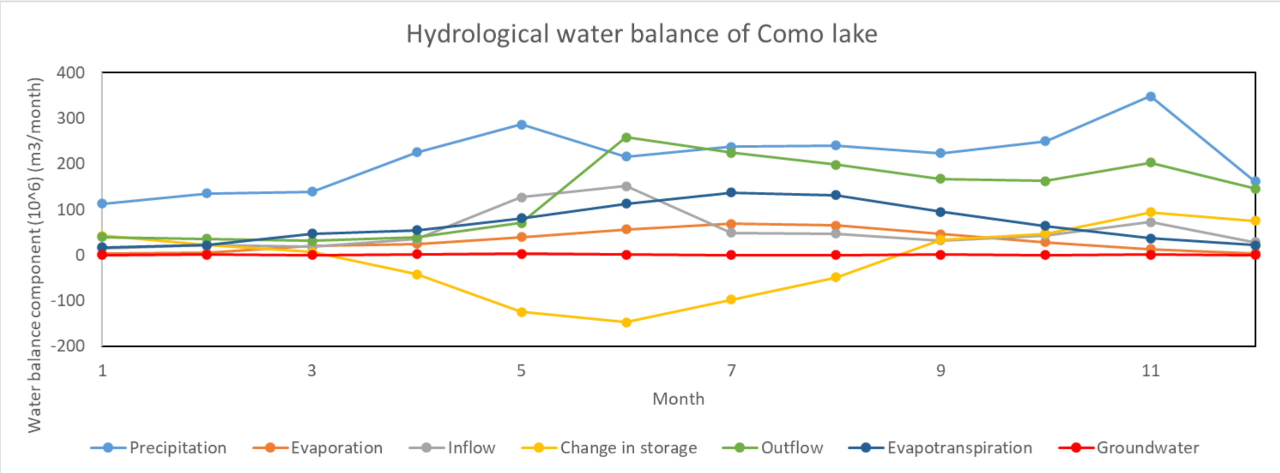


Figure 4.45 *Monthly hydrological balance.*

Precipitations and outflow represent the largest parameters which strongly affects the hydrological balance. Being the ETP (and its components) and the inflow small compared with precipitation and outflow, it is visible how consequently the change in storage depends by the first 2 parameters only. Change in storage is almost overall always negative in the considered period due to precipitation lower than outflow.

It is visible from the balance how due to the possibility, through the dam, to regulate the outflow, there is correlation between the precipitation and the outflow. This is true, except for the summer months where the request of water for irrigation is very large. The evaporation and evapotranspiration in the lake watershed represents the less impactful values.

Interesting is also to analyze the parameters of groundwater which correspond at the amount of water that the lake exchange with the soil and in this parameter is also contained the error of calculations. The groundwater component is very complex to calculate, in fact, it is generally estimated using the hydrological balance. The term is very small compared with the others and it contains the error associated to the model and assumption made in the calculation.

The above balance additionally presents large uncertainties due to the modeling of some parameters and due to the low amount of gauge present.

5. FUTURE SCENARIOS AND ADAPTATION MEASURES

5.1 Future projections

Climate change (CC) has been recognized as one of the most important challenges for the human, in fact it is going to affect both natural and socio-economic systems. CC influences the future approach respect to the use of resources, the implementation of production processes and the human activities in general. But not only, in fact climate change is a global issue affecting the world's hydrology and water resources. Quantifying climate change impacts on hydrology is important for integrated water resources management (Melsew A. Wubneh et all., 2020). To get information and then define strategies to implement from projections, the knowledge of the past data is necessary. So, starting from all the analyzed data, forecasts were made to understand how everything is going to evolve. The aim of forecast estimation is to decide which type of adaptation measures and strategy implement in a specific environment. The developed and the method used was necessary to make and calibrate a baseline to make future projections on track with RCP 4.5 and RCP 8.5. Future projections are related to the streamflow change (Flavia Fuso et all., 2021). Specifically, RCPs are representative concentration pathways which correspond to different values of greenhouse gas concentration defined by IPCC[1]. Four are the scenarios defined but, in our case, it has been analyzed only 2 which are the low-intermediate emission (which correspond to the expected scenario in case in which not significative reduction of emissions there will be) and the worst connected with highest level of emissions (Dessalegn Worku Ayalew et all.; 2022). A lot of methods have been implemented by group of scientists and all of them will be used in a simulation called multi-model ensemble to reduce the uncertainties expected in this forecasting model already plotted. Any model defined by different group of scientists differ from the other for the initial and boundary conditions. The initial condition cope with the data from which the model is elaborated while for what concern the boundary, they depend by a lot of variables (i.e., land and vegetation, aerosols, GHGs, solar forcing,…) (IPCC, 2023).

[1] Intergovernmental Panel of Climate Change https://www.ipcc.ch/

Within all variables that could be analyzed, the most interesting for our purpose are related to temperature and precipitation. The calculation of all parameters will permit to understand and make consideration (and then strategies) to adapt and mitigate the climate change. Focalizing the attention to Lombardy, in the graphs below are represented the variation of temperature and precipitation considering only the most interesting RCP: 4,5 and 8,5. All forecasted data and then indices calculations were performed using CMIP6 data which derive from the Sixth phase of the CMPIs and then it supports the IPCC's Sixth Assessment Report.

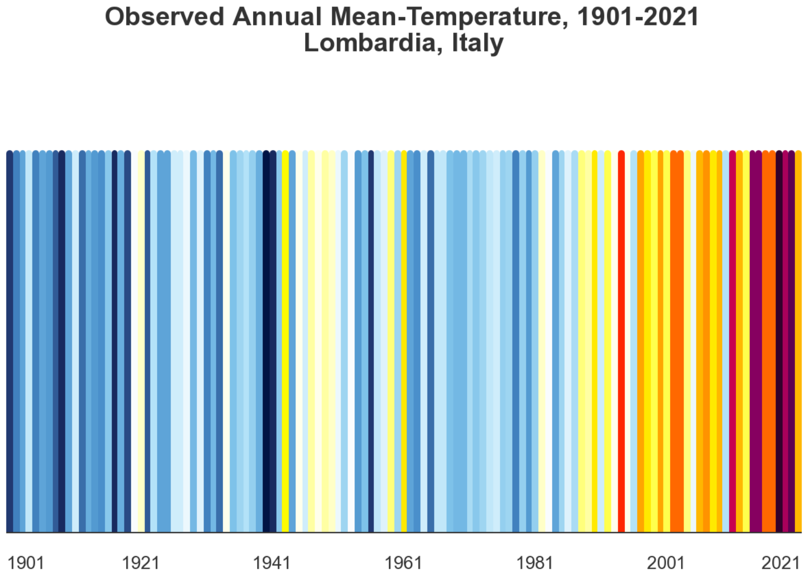


Figure 5.1 *Annual mean temperature observed in Lombardy from 1901 to 2021.*

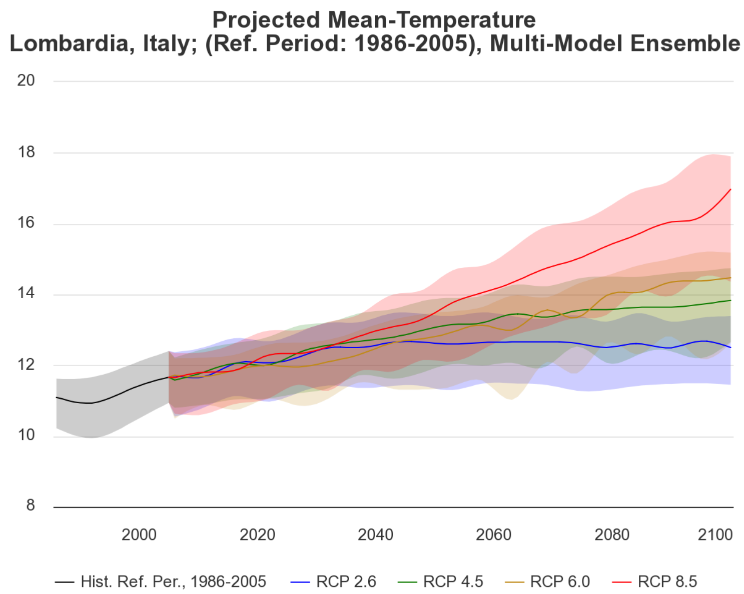
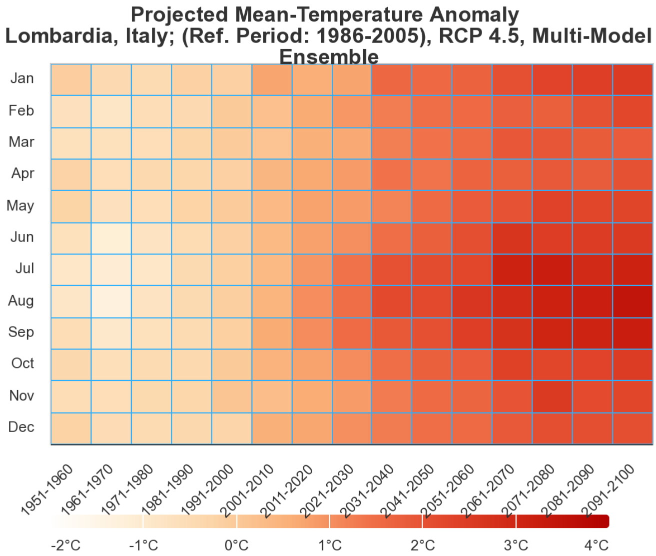


Figure 5.2 *Projected mean temperature anomalies.*



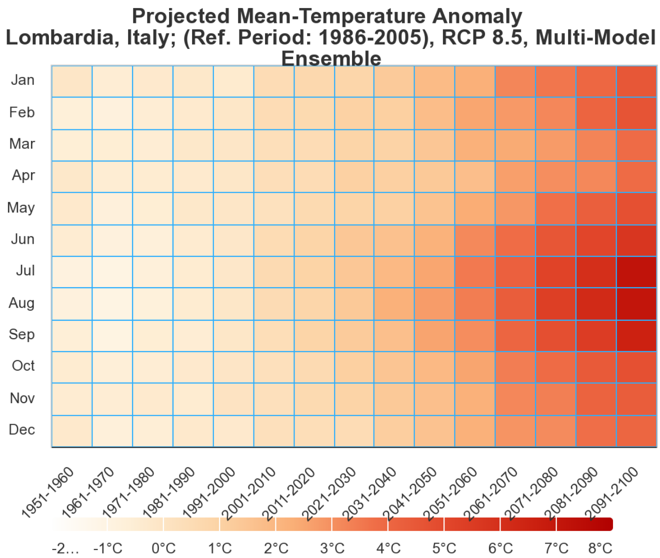


Figure 5.3*Projected mean temperature anomalies for RCP 4.5 (left image) & RCP 8.5 (right image).*

The same type of evaluation has been performed for what concern precipitations:

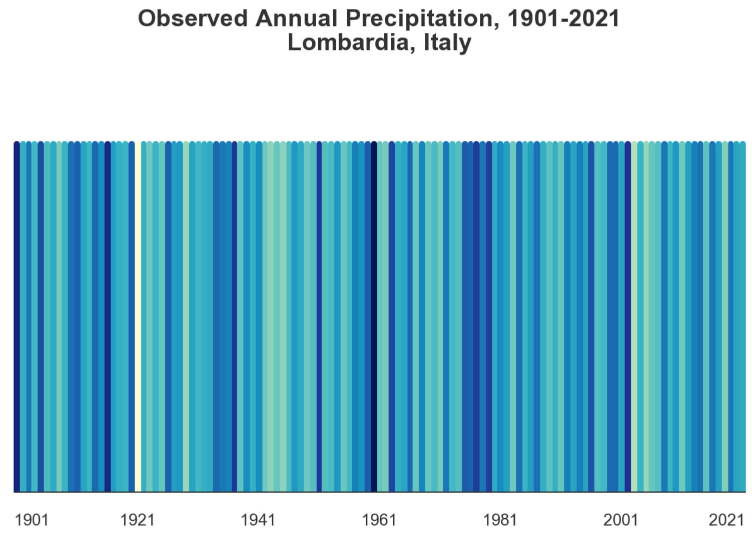


Figure 5.4 *Annual mean precipitations observed in Lombardy from 1901 to 2021.*

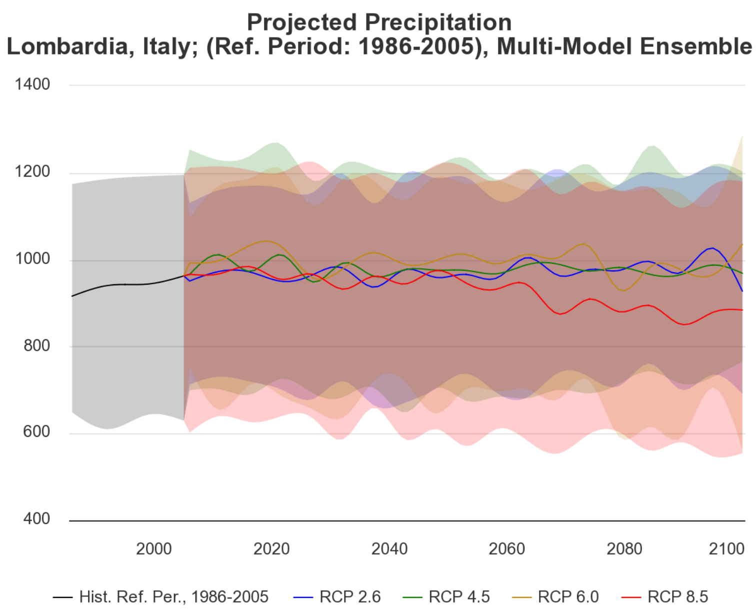
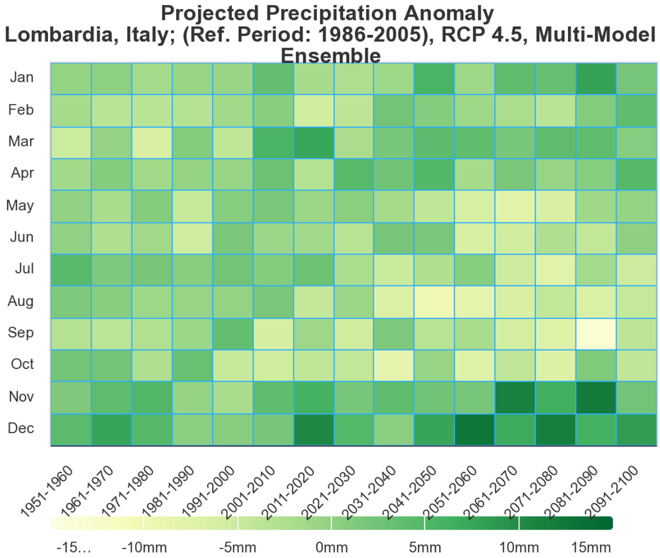


Figure 5.5 *Projected mean precipitation anomalies.*



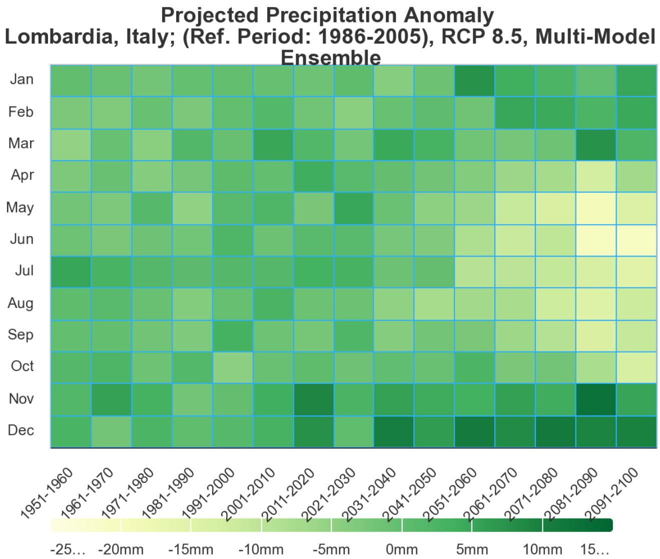


Figure 5.6 *Projected mean precipitations anomalies for RCP 4.5 (left image) & RCP 8.5 (right image).*

From these projections and models, it was possible to extract data and plot them to evaluate indices of extreme with the aim to understand how CC is going to impact. The data used have been extracted from Med-CORDEX association which is a separate section of scientistic which produce RCM (regional climate models) simulations only for the Mediterranean area. Model grids have a resolution of 0.44°x 0.44° and the average resolution is 50 km. It was choosing data from CORDEX with respect to CMIP5 because it permits to study better, and it gives more exhaustive data for RCM model. Only data related to Lombardy have been extracted and elaborated for what concern the projections, while for past evaluation of indices were used the already download data from ARPA.

Specifically, the most interesting indices were calculated as defined by ETCCDI[2] (working group of WMO expert on climate change detection) and all of them was evaluated year by year (Thomas C. Peterson et all., 2001). In this thesis past data were plotted as the average values coming from historical data (from 2008 to 2022) compared with 2 projection periods (from 2030 to 2060 and from 2060 to 2090). All indices estimated are presented in the Table 5.1.

Table 5.1 *Calculated indices.*

Indices	Description	Unit
FD	Numbers of frost days	days
SU	Numbers of summer days	days
ID	Numbers of icing days	days
TR	Number of tropical nights (Tmin>20°C)	days
HD	Number of hot days (Tmax>35°)	days
GSL	Growing season lenght	days
TXx	Monthly maximum value of daily maximum temperature	°C
TNn	Monthly minimum value of daily minimum temperature	°C
WSDI	Warn speel duration index	-
CSDI	Cold speel duration index	-
CDD	Max number of consecutive dry days	days
CWD	Max number of consecutive wet days	days
SPEI	Annual SPEI drought index	-
DPH	Days with precipitation >20mm	days

In this part were calculated and evaluated indices of extreme comparing the one calculated from the past data with 2 sets of projection (from 2030 to 2060 and from 2060 to 2090) considering 2 different scenarios. Specifically, these values have been estimated with larger resolution to be valid for all Lombardy region. The definition of each index is the same as define by ETCCDI.

[2] http://etccdi.pacificclimate.org/list_27_indices.shtml

- Number of frost days – “The average aggregated number of days where the daily minimum temperature is below 0°”.

Period	Past data	RCP 4.5 (from 2030 to 2060)	RCP 4.5 (from 2060 to 2090)	RCP 8.5 (from 2030 to 2060)	RCP 8.5 (from 2060 to 2090)
Value	46	38	30	38	14

- Number of summer days – *“The average aggregated number of days where the daily maximum temperature is above 25°C”.*

Period	Past data	RCP 4.5 (from 2030 to 2060)	RCP 4.5 (from 2060 to 2090)	RCP 8.5 (from 2030 to 2060)	RCP 8.5 (from 2060 to 2090)
Value	68	79	94	81	129

- Number of icing days – *“The variable represents the average aggregated number of days where the daily maximum temperature is below 0°C”.*

Period	Past data	RCP 4.5 (from 2030 to 2060)	RCP 4.5 (from 2060 to 2090)	RCP 8.5 (from 2030 to 2060)	RCP 8.5 (from 2060 to 2090)
Value	7	5	4	5	1

- Number of tropical nights – *“Days with minimum temperature above 20°C”.*

Period	Past data	RCP 4.5 (from 2030 to 2060)	RCP 4.5 (from 2060 to 2090)	RCP 8.5 (from 2030 to 2060)	RCP 8.5 (from 2060 to 2090)
Value	9	16	28	18	78

- Number of hot days – *“The number of days with daily maximum temperature >35°C”.*

Period	Past data	RCP 4.5 (from 2030 to 2060)	RCP 4.5 (from 2060 to 2090)	RCP 8.5 (from 2030 to 2060)	RCP 8.5 (from 2060 to 2090)
Value	-0.1	1.2	4	1	35

- Growing season length – *“The annual number of days between the first span of at least six consecutive days in which the daily temperature is higher than 5°C and the first span in the second half of at least six consecutive days in which the daily mean temperature is below 5°C”.*

Period	**Past data**	**RCP 4.5 (from 2030 to 2060)**	**RCP 4.5 (from 2060 to 2090)**	**RCP 8.5 (from 2030 to 2060)**	**RCP 8.5 (from 2060 to 2090)**
Value	271	274	283	282	320

- Monthly maximum value of daily maximum temperature – *"This variable represents the single-day maximum value of the daily maximum temperatures"*.

Period	**Past data**	**RCP 4.5 (from 2030 to 2060)**	**RCP 4.5 (from 2060 to 2090)**	**RCP 8.5 (from 2030 to 2060)**	**RCP 8.5 (from 2060 to 2090)**
Value	33	34	35	34	40

- Monthly minimum value of daily minimum temperature – *"This variable represents the single-day minimum value of the daily minimum temperatures"*.

Period	**Past data**	**RCP 4.5 (from 2030 to 2060)**	**RCP 4.5 (from 2060 to 2090)**	**RCP 8.5 (from 2030 to 2060)**	**RCP 8.5 (from 2060 to 2090)**
Value	-8	-7	-5	-6	-3

- Warn spell duration index – *"The number of days in a sequence of at least six consecutive days during which the value of the daily maximum temperature is greater than the 90th percentile of daily maximum temperature calculated for a five-day window centered on each calendar day, using all data for the given calendar day-pentad from the data period for a reference climate (e.g., present day climate)"*.

Period	**Past data**	**RCP 4.5 (from 2030 to 2060)**	**RCP 4.5 (from 2060 to 2090)**	**RCP 8.5 (from 2030 to 2060)**	**RCP 8.5 (from 2060 to 2090)**
Value	21	42	95	60	199

- Cold spell duration index – *"The number of days in a sequence of at least six consecutive days during which the value of the daily minimum temperature is less than the 10th percentile of daily minimum temperature calculated for a five-day window centered on each calendar day, using all data for the given calendar day-pentad from the data period for a reference climate (e.g., present day climate)"*.

Period	**Past data**	**RCP 4.5 (from 2030 to 2060)**	**RCP 4.5 (from 2060 to 2090)**	**RCP 8.5 (from 2030 to 2060)**	**RCP 8.5 (from 2060 to 2090)**
Value	1	0	1	1	0

- Max number of consecutive dry days – *"The maximum length of a dry spell, computed sequentially for the entire time series, then taking the maximum value during each month in the data period (a dry day is defined as any day in which the daily accumulated precipitation is less than 1 mm)".*

Period	Past data	RCP 4.5 (from 2030 to 2060)	RCP 4.5 (from 2060 to 2090)	RCP 8.5 (from 2030 to 2060)	RCP 8.5 (from 2060 to 2090)
Value	17	17	19	19	22

- Max number of consecutive wet days – *"The maximum length of a wet spell, computed sequentially for the entire time series, then taking the maximum value during each month in the data period (a wet day is defined as any day in which the daily accumulated precipitation is equal or larger than 1 mm)".*

Period	Past data	RCP 4.5 (from 2030 to 2060)	RCP 4.5 (from 2060 to 2090)	RCP 8.5 (from 2030 to 2060)	RCP 8.5 (from 2060 to 2090)
Value	15	14	13	13	13

- Annual SPEI drought index – *"The annual standardized precipitation evapotranspiration index represents a measure of the integrated water deficit in a location, taking into account the contribution of temperature-dependent evapotranspiration".*

Period	Past data	RCP 4.5 (from 2030 to 2060)	RCP 4.5 (from 2060 to 2090)	RCP 8.5 (from 2030 to 2060)	RCP 8.5 (from 2060 to 2090)
Value	0.10	-0.34	-0.27	-0.32	-1.6

- Days with precipitation larger than 20 mm – *"The number of very heavy precipitation days during the aggregation period. A Very heavy precipitation day is defined as any day in which the daily accumulated precipitation is equal or larger than 20 mm".*

Period	Past data	RCP 4.5 (from 2030 to 2060)	RCP 4.5 (from 2060 to 2090)	RCP 8.5 (from 2030 to 2060)	RCP 8.5 (from 2060 to 2090)
Value	4	4	5	4	5

From the above calculated indices is visible how looking at the projection, in any case, comparing the short-term scenario with the long term, the consequences of CC become stronger and do not follow any proportionality in time. For what concern the scenario

RCP 4.5 moving from 2030 to 2090 the values increased but not so much as in case of worst scenario (RCP 8.5).

Past data compared with forecasts present large gap with respect to future projections, mainly for what concern number of hot days, tropical nights and SPEI droughts index. This is probably because CC is going to impact them strongly.

5.2 Adaptation measures

"Adapting to climate change means taking action to prepare for and adjust to both the current effects of climate change the predicted impacts in the future." [3]

The last step of this thesis was to propose and evaluate in according with the get data and forecast scenarios, measure of adaptation that could preserve and reduce the impact of climate change effects. Specifically, the water preservation was also related to guarantee a certain amount of additional water for human purpose (i.e., electricity generation, irrigation ,..). A lot of different strategies and measures could be implemented in according with the ecosystem and the environmental characteristics of a place under analysis to improve resilience (Fang Wang et all., 2023). Using the scenarios already defined in the paragraph 5.1, it has been investigating potential adaptation strategies in their responses considering the economic, environmental, and social dimensions of sustainability in a developed countries like Italy highly vulnerable to CC and to its impact (Judy Rogers et all.; 2021).

Any measure that could be implemented in the lake was performed with the aim to address a variety of adaptation outcomes to decrease the impact on human, environmental and ecosystem dimensions (Camila I. Donati et all., 2019; J. Crossman et all., 2012).

A specific and focalize strategies for the lake under analysis will be performed considering its origin which is glacial and then strongly affected by climate change as all mountain environments. Such knowledge and awareness can be an important driver of both climate adaptation and any environment impact to reduce and to counteract the degradation due to climate change (Hannah Marcus et all., 2013).

[3] European commission

5.2.1 Como Lake adaptation strategies

From already processes data and the get results, t has been defined some adaptation strategies that could be implemented to Como lake. Within all strategies that could be made, three macro categories of interventions are below proposed:

1. Maintain water quality and availability

   It is necessary to guarantee enough water to permit large release into the Adda river for agricultural purpose and electricity production. The quality is mainly related to the possibility of eutrophication being a lake that receive water only from precipitations and inflows from rivers. In this specific case being the lake very large and characterized by currents, the main cause of pollutant and eutrophication is due to release of contaminant in the river. Then, make a strong local monitoring through cameras and people which control could totally reduce this type of problem.

   For what concern the maintenance of water availability, being present dams, the best thing that could be done is to make forecasts in water amount and its fluctuation in time to manage water to guaranteed at least the minimum environmental level amount necessary for the ecosystem to survive and at the same time water for agriculture and hydropower plants use.

2. Enhance local monitoring

   The local monitoring is complementary and necessary to manage the water availability in the best way possible making also forecasts and creating a monitoring system to control the hydrology of lake, to collect data and to use them for better previsions.

3. Preserve habitat

   To maintain habitat is necessary to preserve all species (animals and plants) that live in this environment. A lot of different interventions could be made but in this specific case it could be restored some riverbanks and floodplains to reduce erosion and buffer from extreme flooding while creating seasonal habitat for wetland creatures. This strategy can be performed both where cities are present and not. Additionally, to that, areas where critical habitats are present can be protected and the community educated to promote the importance of ecosystem preservation.

6. CONCLUSION

In this thesis the hydrological balance of Como lake and some adaptation methodologies have been investigated. Starting from hydro-meteorological data used in this study, it has been estimated and elaborated all other parameters necessary to perform the hydrological balance which results provide the basis for a further investigation on future projections of lake hydrological behavior.

Precipitation, air temperature and hydrometric level data were extracted from 01/08/2008 to 16/04/2023 from ARPA Lombardy database. Starting from these data, through the usage of stage-discharges curve, inflows and outflow values have been estimated. Not being enough the available data, for the inflows, HBV model has been used. In particular, the parameters used to estimate the inflows were referred to the Adda and Mera watersheds.

Additionally, the evaporation of the lake and the evapotranspiration of the watershed have been calculated using respectively Penman equation and Hargreveas-Samani.

Then, with all these data a monthly hydrological balance of the lake was defined.

The main limitation was related with the low number of gauges present and some assumptions made for the HBV model application. Specifically, it derives that HBV only partially was able to describe and define the watershed analyzed. This conclusion derives from the fact that the best calibration and validation of the model were far from the value of one for both the parameters R_{eff} and *KGE.* According to this, it is possible to say that the application of HBV model for our specific purpose fits partially well; in fact, it is possible to think about using or even creating other software which can better describe the Italian lakes characteristics.

Then, the hydrological balance of Como lake has been performed. Analyzing the result, it is visible how the water balance of the lake and its watershed is mainly influenced by the precipitation, outflow, and inflows from other watersheds. Evaporation, evapotranspiration and groundflow terms are almost negligible with respect to other terms while the change in storage is more significant. Specifically, this last parameter present negative values during spring/summer months. This variation is due to the larger request of outflow for the irrigation of the valley and lower amount of precipitation.

After those preliminary studies, starting from the past data and using forecast data from CMPIs database, climate change indexes have been estimated comparing past data with future values looking at 2 different scenarios: RCP 4,5 and RCP 8,5.

Clearly, this specific study for Como lake could be extended to other lakes changing boundary and initial conditions. This thesis was only the beginning of a big project based on the possibility to manage the Po water resources and then find the best adaptation strategy for the overall Po valley.

The idea is to improve water management. Security and climate resilience though a lot of methodologies that could be implemented after initial elaboration of data such as hydrological balance. On the other hand, the main limitations for this type of methodology are the largest amount of data that should be elaborated and the necessity to define a model which is able, by changing the main conditions, to represents the watershed under analysis and replicate the same conditions as in the reality.

So, this type of study could be used related to future prospective to make climate adaptation strategies a permanent part of the Po valley management.

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