POLITECNICO DI MILANO

Facoltà di Ingegneria

Scuola di Ingegneria Civile, Ambientale e Territoriale

Master of Science in

Environmental and Land Planning Engineering

The role of snow information in improving water management: the lake Como case study

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Academic Year 2012-2013

ACKNOWLEDGMENTS

I would like to thank Professor Andrea Castelletti for the valuable teachings and for the hours devoted to my thesis. In addition, I sincerely thank Professor Enrico Weber, who has always been available to settling my doubts during the course of this work, and Dr. Matteo Giuliani for his help.

I want to thank ARPA Lombardia, emphasizing the particular availability of Dr. Dario Bellingeri, for providing me the information needed for the realization of the thesis.

Finally, the deepest gratitude to my family who has always supported me and gave me the opportunity to reach this goal.

Last but not least, a thanks straight from my heart to Ilaria for supporting me during these years of study with trust, understanding and, above all, with love.

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ABSTRACT

This study presents a criteria for the selection of variables to be used for the management of regulated lakes. Historically, the regulator of Lake Como uses the information derived from the knowledge of inflows and storage of the lake. In this document we are going to look for other possible variables, in particular those derived from knowledge of the snow water equivalent, which may be able to improve the management of the lake. After determining the best set of controls using deterministic programming, it was used a Variable Selection algorithm to calculate the available variables which best fits these controls. The results obtained show that in the top positions of the selected variables are present, in addition to the storage of the mountain hydroelectric reservoirs, the variables derived from the knowledge of snow water equivalent present in the basin of the Adda. Using these variables it was fed a Direct Policy Search algorithm combined with a Multi-Objective Evolutionary Algorithm to obtain the Pareto frontiers in function of the type and number of variables used. In this way it was possible to obtain the degree of improvement in the management of the lake compared to the current policy.

ESTRATTO

Con la costruzione della diga di Olginate nel 1946, il lago di Como è diventato un bacino regolato. Il suo principale affluente, e anche unico emissario, è il fiume Adda, che raccoglie le acque di un vasto bacino imbrifero comprensivo delle zone dell'alta Lombardia e di alcuni territori del sud della Svizzera. Questi territori sono prevalentemente montuosi, ad eccezione delle valli in cui scorrono i principali corsi d'acqua. Durante l'inverno la precipitazione è prevalentemente nevosa e durante il suo scioglimento, in primavera, si crea una grande quantità di acqua che scende verso il lago. Dal momento della costruzione della diga le sue acque sono state oggetto di forte contesa tra le società elettriche che sfruttno i rilasci per produrre energia, i contadini a valle che in certi periodi dell'anno chiedono considerevoli quantità di acqua per l'irrigazione, e i rivieraschi, che vorrebbero evitare le esondazioni e contemporaneamente, in estate, avere il lago ad un livello abbastanza alto per la balneazione e quindi per il turismo. Si capisce quindi come la regolazione del lago sia sottoposta a numerose pressioni da parte di vari attori in gioco e come una migliore gestione dei rilasci, e i conseguenti benefici di tutte le parti coinvolte, costituisca un obiettivo rilevante.

La domanda che ci si è posti è quindi se la conoscenza della quantità di neve presente nell'arco Alpino connesso al bacino del lago di Como sia di aiuto alla gestione del lago stesso. Più in generale ci si è chiesto quali siano le informazioni con cui migliorare la gestione del lago di Como, e se tra queste ce ne sia qualcuna correlata alla conoscenza della quantità di neve immagazzinata in quota.

Attraverso questa ricerca non si ha certo la pretesa di esaurire l'argomento; tuttavia il lavoro svolto è stato utile per capire se la conoscenza di alcune informazioni dia la possibilità di aumentare la soddisfazione di tutti gli attori coinvolti. Sarà poi compito dei soggetti interessati valutare la completezza di questa ricerca e, se necessario, continuare gli studi in questa direzione.

Dopo aver calcolato la miglior serie di controlli sul periodo preso in esame, ovvero quello compreso tra il 2007 e il 2011, mediante la Programmazione Deterministica, si è utilizzato un algoritmo di Variable Selection per individuare le migliori variabili a disposizione. I risultati ottenuti hanno risposto affermativamente alla domanda che ci si era posti poiché nelle primissime posizioni si trovano, oltre che gli invasi dei serbatoi elettrici montani, anche le variabili che derivano dalla conoscenza dell'equivalente idrico della neve presente nel bacino dell'Adda. Utilizzando queste variabili si è alimentato un algoritmo di Direct Policy Search combinato con un modello Evolutivo

Multi-Output per ottenere le frontiere di pareto in funzione delle informazioni utilizzate. Si è qiondi misurato il grado di miglioramento rispetto alle politiche attuali.

1 INTRODUCTION

With the construction, in 1946, of the dam in Olginate, the lake of Como has become a regulated reservoir. Its main tributary, and also the only effluent, is the river Adda, which collects the waters of some vast catchment areas including the upper Lombardy and some parts of southern Switzerland. These areas are mostly mountainous, with the exception of the valleys where the main streams flow. In winter the precipitation is mostly snow, and during its melting, in spring, it creates large amounts of water that goes towards the lake. The waters of the lake have been cause of heavy contention between the electricity companies, that use releases to produce energy, the farmers in the valley, that in certain periods of the year require large amounts of water, and riparians inhabitants, who would avoid flooding and, at the same time,in summer, would have the lake to a level high enough for bathing and for tourism. So we understand how the regulation of the lake is subject to numerous pressures from various players and how better release management can bring benefits to all parts involved.

The question that has been placed is whether the knowledge of the amount of snow over the connected basin of Lake Como can aid the management of the lake itself. In general,we wondered what the information with which improve the management of lake Como are, and if, among these information, there was someone related to the knowledge of the amount of snow stored in the mountains.

Through this research we certainly do not pretend to exhaust the subject, but the work has been useful to understand if the knowledge of particular information offers the possibility to increase the satisfaction of all stakeholders. The involved subject will then evaluate the reliability of this research and, if necessary, will continue the studies in this direction.

The work consists of three chapters besides the introduction and conclusions: In the second chapter there is the description of the followed methodology and the formulations of the problems. There is also a description of the lake, all the catchment areas and all mountain reservoirs with a focus on the owners and on the watersheds.

In the third chapter there are the definitions of the "free" and "connected" Snow Water Equivalent and there is the study of snow data acquisition methods and the transformation of the same data in snow water equivalent by Arpa Lombardia. Then, is carried out the analysis of the main parameters that are considered suitable to improve the management, among which can be mentioned, in addition to swe, the melting of the snowpack, the main parameters of hydroelectric reservoirs in the basin of the Adda, the snowfall and the rain fall in the territory, the altitude of the freezing point, the time and also the parameter that is used today by the controller of the dam: the level of the lake recorded by the hydrometer of Malgrate.

In the fourth chapter, in order to compare the performance of each parameters, is determined the best control policy using the deterministic programming. Then, is used a decision algorithm able to create a ranking of the best variables and their degree of adaptation to the controls derived from deterministic programming. The results is then passed to a regression algorithm that obtains the sequence of measured controls, which are compared again with the results of the deterministic programming to verify their correctness. As last experiment, the best data are used to feed an optimization algorithm of lake Como able to provide a sequence of Pareto frontiers in function of the type and number of inputs used. These frontiers are compared between themselves and with that resulting from deterministic programming, to verify which inputs provide an improvement of the management of the dam of Olginate.

2 MATERIALS AND METHODS

2.1 METHODOLOGY

The hydroclimatic information are usually used to build inflow models that are used to design more informed decisions. Despite this, the same information can be used to direct feed the water resource systems operation without the intermediation of physical models.

In order to determining which are the best available information suitable to replace the knowledge of the inflow, it was necessary to establish the optimal controls trajectory. This can be obtained assuming that the maximum possible information available to the decision-maker is the perfect knowledge of all present and future hydrological conditions. This operation can be designed by deterministic optimization.[6] The series of optimal controls is not unique because they depend on the importance given to each of the objectives defined during the deterministic programming. So it is possible to generate a Pareto frontier, which is the set of best available solutions.

Once this Pareto frontier has be obtained, comparing it with that derived from the historical policy, the space of possible improvement of the goals that can be reached by the use of hydroclimatic information, can be identified. In order to reach this space, as we said early, the first step is to determine which, among the candidate input variables, is most effective as a surrogate of the future inflows for operation purposes.

The selection among such variables it was carried out with an Input Variable Selection algorithm. This algorithm is based on tree models, and is able to automatically perform the ranking of the variables because its particular structure can be exploited to infer the relative importance of the input variables and to accordingly sort them. Every variables is used as inputs for Single Input, Single Output models (SISO), in order to rank the candidates on the variance. The evaluation of each model input is via *k-fold cross-validation*: the data set is divided into k subsets of equal size and filled randomly. The SISO model is run *k* times, each time using a different subset in validation, while the remaining *k-1* subsets are used for calibration. The performance of the model will then be the average of the performance of individual submodels so evaluated. A multi-input single output model (MISO) is then used, adopting the variables chosen so far, to evaluate the performance and the output achieved. The procedure is repeated using as new output the residues between the desired output and the output of the MISO model until the best candidate is not a variable already contained in the set of those chosen, or until the performance of the MISO model don't significantly improves or worsens. At this point the best variables are those contained in the set chosen by the algorithm that provides an estimate of the output with performance equal to the final performance of the MISO algorithm (former to the one obtained for termination of the algorithm itself).

The last step is to assess the actual value of the selected variables for the system operation. To this purpose, it is decided to use a Direct Policy Search combined with multi-objective evolutionary algorithms, in order to solve high-dimension state and control space problems and find an approximation of the entire Pareto front, and the associated control policies, in a single optimization run.[5] The multi-objective optimization of the policy parameters is performed using the self-adaptive Borg MOEA, which has been shown to be highly robust across a different suite of challenging multi-objective problems.

2.2 PROBLEMS FORMULATION

2.2.1 *Deterministic optimization*

The deterministic optimization problem is:

$$\min_{\mathbf{u}} J(\mathbf{x}_0, \mathbf{u}, \mathbf{q}) \qquad \text{s.t. } (\mathbf{x}_0, \mathbf{q}) \text{ given}$$

where $\mathbf{u} = |\mathbf{u}_0, ..., \mathbf{u}_{h-1}|$ is the sequence of decisions to be taken over the optimization horizon $[0, h-1]$, and J is the objective function (cost) whose value also depends on the initial state $\mathbf{x}_0$ (e.g. the reservoir storage) and the trajectory $\mathbf{q} = |\mathbf{q}_1, ..., \mathbf{q}_h|$ of the uncontrolled inputs (e.g. reservoir inflow) over the optimization horizon. The solution $\mathbf{u}^*$ of problem is optimal under the given trajectory $\mathbf{q}$ of uncontrolled inputs.

The problem can be solved either by non-linear programming (NLP) methods (e.g. gradient-based or direct search methods) or by deterministic dynamic programming (DDP). In this work, DDP was used because it is computationally efficient and provides very accurate solution.[6]

2.2.2 *Input Variable Selection*

The optimal release sequence $\mathbf{u}^*$ generated by deterministic dynamic programming is conceptually equivalent to a feedback operating rule of the form:

$$\mathbf{u}_t = \mathbf{m}(\mathbf{x}_t, t, \mathbf{q}_{t+1}, \mathbf{q}_{t+2}, ..., \mathbf{q}_h)$$

The future sequence of inflow must be replaced by a vector $\mathbf{I}_t$ of hydroclimatic variables selected in such a way to characterize as much accurately as possible the optimal sequence $\mathbf{u}^*$. It is used the tree-based Iterative Input Selection (IIS) algorithm, which is a model-based input selection algorithm that holds three features particularly useful in the problem we are dealing with: flexibility (i.e. the ability of modelling strongly non-linear functions), computational efficiency (i.e. the ability of processing large data-sets), and scalability with respect to the input dimensionality (i.e. the ability of handling several input variables with a different range of variability). [6]

2.2.3 *Policy design*

Once the hydroclimatic information vector $\mathbf{I}_t$ has been selected, the next step in our procedure is the identification of an optimal operating rule conditioned upon this information, i.e.

$$\mathbf{u}_t = \mathbf{m}(\mathbf{x}_t, t, \mathbf{I}_t)$$

The methodology for the resolution of this problem involves the selection of a prescribed function family $\hat{\mathbf{m}}(\cdot)$ for the operating rule and then the identification of the optimal parametrization θ^*. [6] In other terms, the optimization problem is reconducted to the following non-linear programming problem

$$\min_{\theta} J(\mathbf{x}_0, \theta, \mathbf{q}) \qquad \text{s.t. } (\mathbf{x}_0, \mathbf{q}) \text{ given and } \mathbf{u}_t = \hat{\mathbf{m}}(\mathbf{x}_t, t, \mathbf{I}_t; \theta)$$

2.3 STUDY SITE

2.3.1 *The lake of Como*

Lake Como, also called Lario, is a natural lake formed due to the withdrawal of the "glacier abduano". It's the third largest Italian lake, with 145 km^2 , and the fifth largest lake in Europe for depth with its 140 meters, after four Norwegian lakes. Its catchment area is divided into three different parts: the branch of Como in the south-west, the branch of Lecco in the south-east, and the north branch of Colico, which give it the shape of an inverted Y. The lake is surrounded by mountains, the highest of which is Mount Legnone (2609 m) above Colico. The tributary waterways are 37, among which the most important is Adda, followed by Mera. Adda is also the only emissary; leaves the lake in Lecco and, after forming the lakes of Garlate and Olginate, continues in the direction of the Po river.

The waters of Lake Como have been exploited since ancient times, it seems that they were used by the Romans around the first century BC. Its early works were simple derivation, with very limited flow of water, that exclusively served the farmers downhill. The works became more and more important with the growth of the cultivated

Figure 2.1: View of the Olginate dam

lands, and when the use of the river for transportation became a crucial means for trade, began works for the construction of channels.

With the continued growth of the riparian population, the problem of flood detention became important, and, with the advent of industry, became essential the production of hydroelectric power. To tackle these two problems, was initially given permission to Edison to build a temporary dam at the outlet of the lake. Then, in the years 1943-44, was reached the construction of the actual dam in order to allow the proper exploitation of water resources by all downstream users, who had gathered in a consortium, the consortium of Adda, in 1938.

The dam shown in Figure 2.1 was built with compressed air foundations, is about 150 m long and is divided into 8 lights of 14 m each, with a threshold of 195 m a.s.l. The lights are closed by flat roller gates, 4m high, which can be operated both electrically and manually. [9]

The maximum available storage of the reservoir (between -0.40 m 1.30 m to the Malgrate hydrometer), adding the 246.5 Mm^3 of Lake Como and 7.8 Mm^3 of Lake Garlate, is 254 Mm^3 .

2.3.2 *The catchment area of the Adda*

The catchment area of the Adda river has a total area of 7927 Km^2, 94% of which falls within the Italian territory, while the remaining 6 % falls into Swiss territory. The basin can be divided into several subbasins: Adda above the lake (Valtellina and Chiavenna), Lake Como, Adda under the lake, Brembo and Serio. For this project have been used only the basin of the upper Adda and the Lake Como.

The basin above the lake can be further divided into two sub-basins where the main waterways are the primary structure of the drainage network of the study area:

- Adda basin (2646 Km^2)

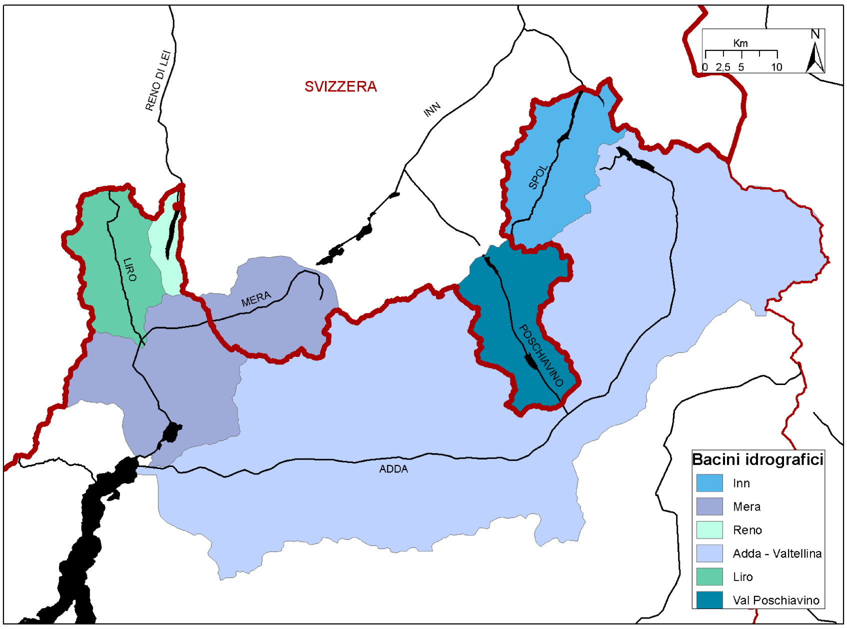


Figure 2.2: The catchment area of the Adda river

- Mera river basin (757 Km^2)

In this basins fall numerous special characteristics shown in Figure 2.2. Val Poschiavo, with an area of about 223 Km^2 , lies entirely on Swiss territory; the source of the river Mera and its initial part falls in Swiss territory; the river Spoel is in Italian territory but, being a tributary of the Inn River, falls in the catchment area of the Danube. Despite this, from its stream are derived up to 90 Mm^3 of water per year, which are discharged into the lake of San Giacomo, re-entering into the basin of the Adda.[21]

2.3.3 *The hydroelectric mountain reservoirs*

From the beginning of the century, numerous works have been carried out for exploitation of water resources in the portion of the basin of the upper Adda, that today constitute a complex system of reservoirs for hydropower production.[1]

The Figure 2.3 presents the location and the list of mountain reservoirs considered. In the following paragraphs we will see the main characteristics of each basin divided by user company,. For a quick reference, the same information is collected in the Table 2.1 in Section 2.3.4.

2.3.3.1 *A2A hydroelectric reservoirs*

A2A has an extensive hydraulic network for collection and distribution of water to the Valtellina hydroelectric power plants. Cancano

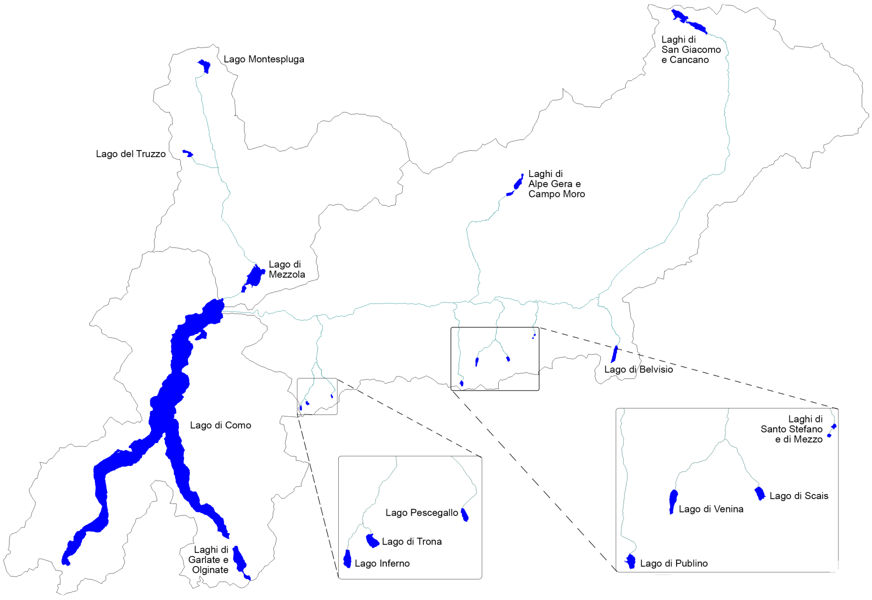


Figure 2.3: Main mountain lakes considered

and San Giacomo are the main mountain reservoirs and are placed in succession as shown in Figure 2.4.

Lakes of San Giacomo and Cancano
The lakes of San Giacomo, Figure 2.5a, and Cancano ,Figure 2.5b, are two contiguous artificial reservoirs, located in the Valley of Fraele in the municipality of Valdidentro, not far from Bormio.

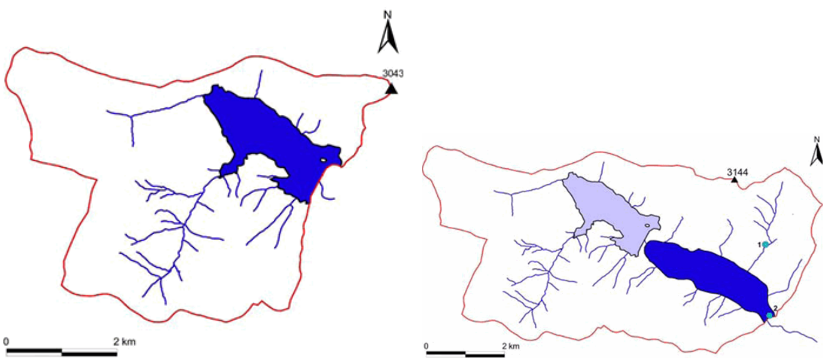
The lake San Giacomo has a maximum storage of 64 Mm^3 of water and the altitude of the top of his dam is located at 1951.5 meters a.s.l. Its basin is fed by the channel Spöl, by the streams Alpe, Gavia, Frodolfo, Zebrù , Braulio and Forcola, as well as from the river Adda. Overall has a catchment area of 18.7 Km^2 and a connected basin of 255.6 Km^2 .

The lake Cancano has a capacity of 124 Mm^3 of water and the altitude of the top of the homonymous dam is located at 1902 meters. Its basin is fed by water coming from the reservoir of San Giacomo and the new channel Viola. Considering the entire catchment area (and thus also the same reservoir of San Giacomo), the catchment area of the lake Cancano is equal to 36 Km^2 while the connected one is equal to 322.3 Km^2 (in this case is considered connected to the lake Cancano even the catchment connected to Lake San Giacomo).

2.3.3.2 *Edipower hydroelectric reservoirs*

These reservoirs are located in Valchiavenna, between the northern tip of Lake Como and the Spluga Pass, and are located along the rivers Liro and Mera. The river Liro springs out from a mountain near the Spluga Pass by peaks over 3000 meters and, after a journey of about 25 km, flows into the river Mera near Chiavenna. The river

Figure 2.4: Diagram of the hydraulic network of a2a



(a) Lake San Giacomo

(b) Lake Cancano

Figure 2.5: Watersheds of the lakes in the a2a network

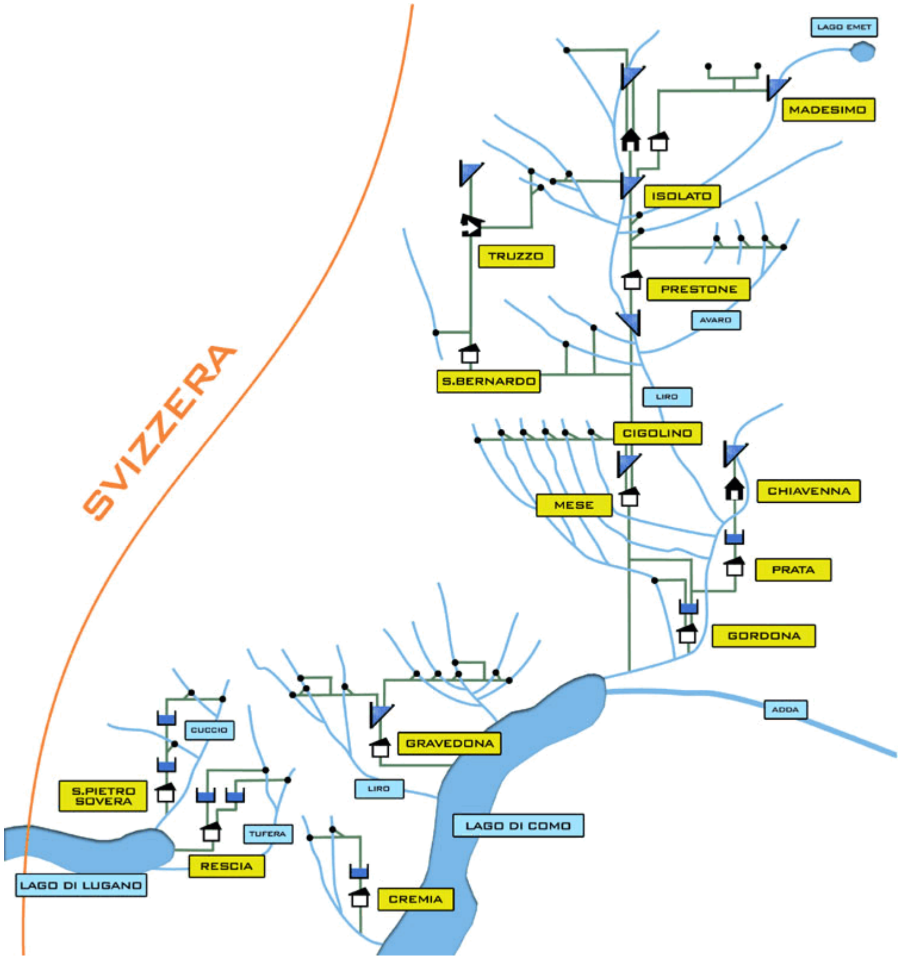


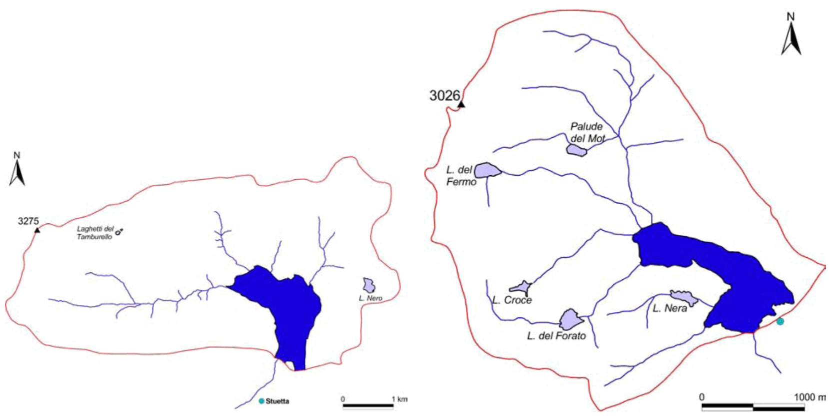
Figure 2.6: Schematic of the hydraulic network of Edipower

Mera comes at over 2800 meter above sea level, in the Swiss territory, and enters the Italian one in Castesegna. The particular exposure and conformation of the two valleys, Liro and Mera, in which are channelled the humid currents from the lake of Como, produces plentiful rainfall.

Lake Montespluga
Located in Upper Valchiavenna, among Madesimo and the Spluga Pass, Lake Montespluga, with an area of 1.7 Km^2 and an average depth of 19.3 meters, is formed by the waters of the river Liro and is closed to the south by two dams, Stuetta and Cardanello, which have an altitude of the top of dam of 1903.5 meters above sea level.

The lake has a catchment area of 24 Km^2 and a connected basin of 2.85 Km^2 , moreover has a maximum storage of 32.6 Mm^3 .

Lake Truzzo
Located in the valley of Drogo, a perpendicular valley to Valchiavenna, Lake Truzzo, has an area of 0.72 Km^2 and an average depth of 23.6 meters. Both the lake and the dam take their names from the river that flows through the valley.



(a) Lake Montespluga **(b)** Lake Truzzo

Figure 2.7: Watersheds of the lakes in the Edipower network

The dam has an altitude of 2088 meters a.s.l. and generates a catchment area of 10 Km² and a connected basin of 5.5 Km² shown in Figure 2.7b. The maximum storage is 20 Mm³ .

2.3.3.3 *Edison hydroelectric reservoirs*

Edison's facilities in the area of Valtellina, built between the 20s and 60s (ex Falck steelworks), consist of two hydraulic links: link Venina-Armisa (5 power plants and 5 dams) and link Ganda-Belviso (2 power plants and 2 dams) plus 2 power plants and two dams in the sub area of Alto Lario.

The reservoir of Frera, connected to the Ganda power plant (Figure 2.8), and the set of lakes from link Venina-Armisa (Figure 2.9) have particular importance.

Lake Belvisio

Lake Belviso, shown in Figure 2.10a, is born from the construction of the dam Frera, which collects the waters of the river Belvisio and some side valleys such as Val del Lat, Val del Camp and the Pisciul.

The lake has a surface area of 1.1 Km² and, thanks to the presence of numerous valleys, has a catchment area of 27.3 Km² , and a connected basin of 20.1 Km² . The altitude of the top of the dam is 1486 meters above sea level and, with an average depth of 45.5 meters, this lake has a maximum storage equal to 50.1 Mm³ .

Lake Venina

Lake Venina, (Figure 2.10b), owes its name to the river that flows above it; has a surface area of 0.4 Km² and an average depth of 28 meters. It's an artificial lake that, thanks to the dam at an altitude of 1824 meters a.s.l., is able to contain a maximum storage of 11.2 Mm³ of water.

Subtended to this lake there is a catchment area of 8.3 Km² , while the connected basin is equal to 11.8 Km² .

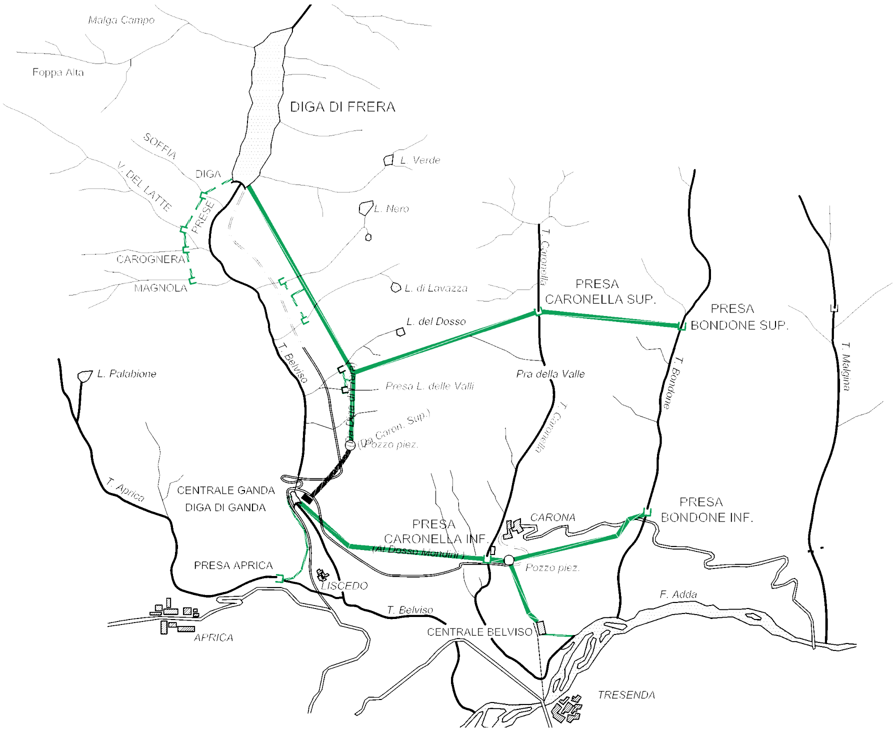


Figure 2.8: Diagram of the hydraulic network of Edison (link Ganda-Belvisio)

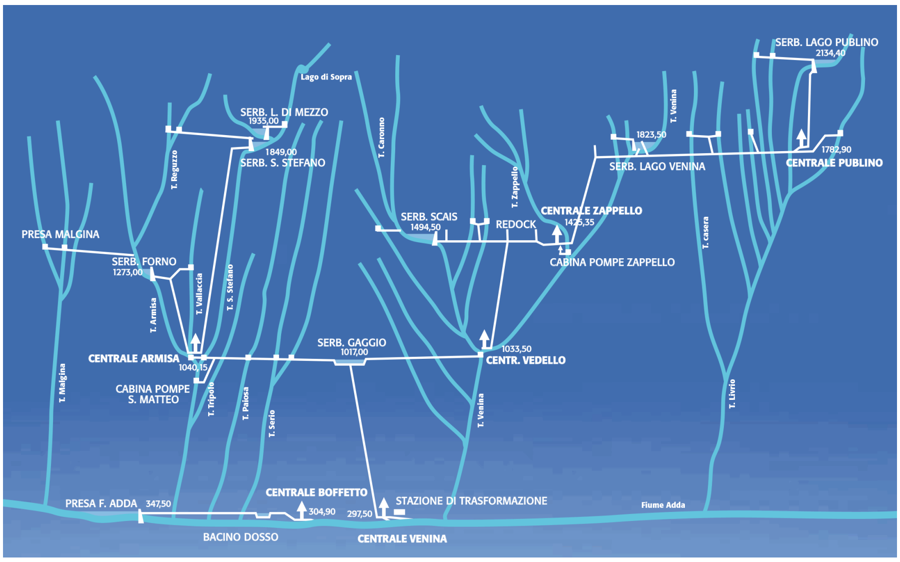
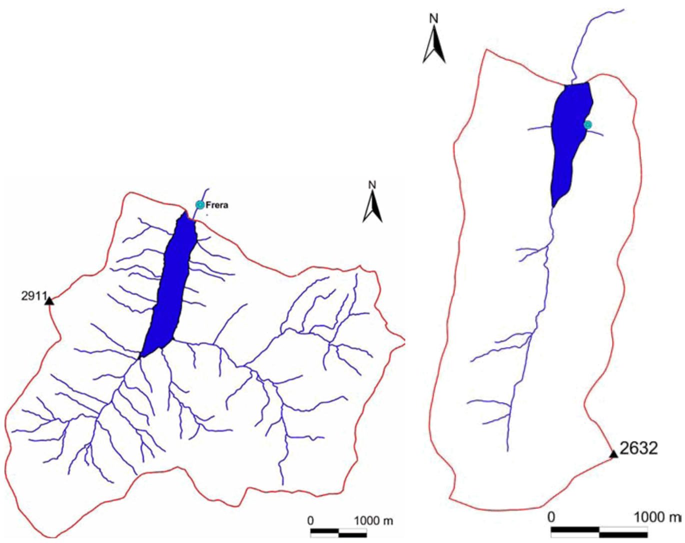


Figure 2.9: Diagram of the hydraulic network of Edison (link Venina-Armisa)



(a) Lake Belvisio **(b)** Lake Venina

Figure 2.10: Watersheds of the major lakes of the network of Edison

Lake Scais
Lake Scais (Figure 2.11a) is located in Val Caronno and was originally a pasture, with lots of houses, which has been flooded after the construction of the dam at an altitude of 1946 meters a.s.l.

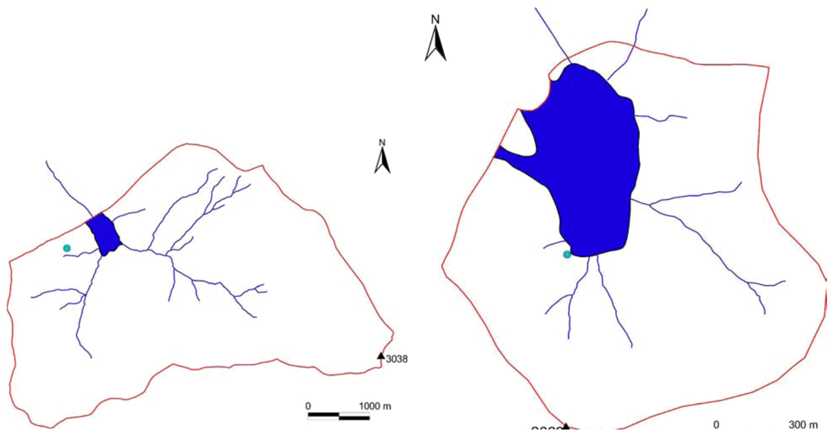
This lake has a catchment area of 17.8 Km^2 and a connected basin of 34.9 Km^2 that allow a maximum storage of 9.06 Mm^3 contained in a surface of 0.25 Km^2 .

Lake Publino
Formed by the waters of the river Livrio, and closed by a small dam at an altitude of 2135 m a.s.l., this lake has a surface area of 0.27 Km^2 and an average depth of only 19 meters. The catchment area of this lake is 1.89 Km^2 while the connected basin is 0.5 Km^2 . Both of them are shown in Figure 2.11b. Because of small catchments, the maximum storage of this pond is 5.185 Mm^3 .

Lake Mezzo and lake Santo Stefano
These two lakes are the smallest considered in this paper and were chosen because they are part of the connection Venina-Armisa Edison hydroelectric power plants.

The two lakes are placed in sequence and are formed by the waters of the river Armisa. The Lake Mezzo is located at an altitude of 1936 meters and has a maximum storage capacity equal to 0.49 Mm^3 while Lake Santo Stefano is situated at an altitude lower than 1850 meters, and has a maximum storage of 0.626 Mm^3 .

The catchment area of these two lakes is equal to 1.9 Km^2 while the connected basin is 1.6 Km^2 .



(a) Lake Scais **(b)** Lake Publino

Figure 2.11: Watersheds of the smaller lakes of the network of Edison

2.3.3.4 *Enel hydroelectric reservoirs*

Enel facilities are divided into two rods. The first one connects the reservoirs of Alpe Gera and Campo Moro to their respective power plants and then move on to the power plant of Lanzada and Sondrio (Figure 2.12). The second one connects the lakes of Inferno, Trona and Pescegallo first to the power plant of Trona and then to the power plant of Gerola Alta (Figure 2.13).

Lake Alpe Gera e Campo Moro

The lake Alpe Gera and lake Campo Moro are located in the upper part of the valley of Campo Moro and are fed by the waters that come down from the Fellaria glacier, across the creek Lanterna.

Alpe Gera is the first reservoir encountered. It is situated at an altitude of 2128 meter and its waters are intercepted by the lake Campo Moro, located at a altitude of 1969 meters. Overall these two lakes have a catchment area equal to 39.9 Km^2 , and a connected basin of 50.9 Km^2 , shown in Figure 2.14a and in Figure 2.14b. These characteristics allow them to have a maximum storage of 68.1 Mm^3 and 10.8 Mm^3 , as regards the lake Alpe Gera and the lake Campo Moro respectively.

Lake Inferno

The lake is located between Pizzo Varrone (2325 m.), Pizzo dei Tre Signori (2554 m.) and Pizzo Trona (2510 m.). So we are close to the border between the provinces of Sondrio, Lecco and Bergamo. It is located at an altitude of 2088 meters and is closed to the north by a dam that is capable of holding a volume of 4.17 Mm^3 . Formed by the waters of the river Inferno, this lake has a catchment area of 1.1 Km^2 and a connected basin of 0.25 Km^2 . Its waters are discharged in the direction of Lake Trona.

Figure 2.12: Schematic of the hydraulic network of Enel (connection Alpe Gera - Sondrio)

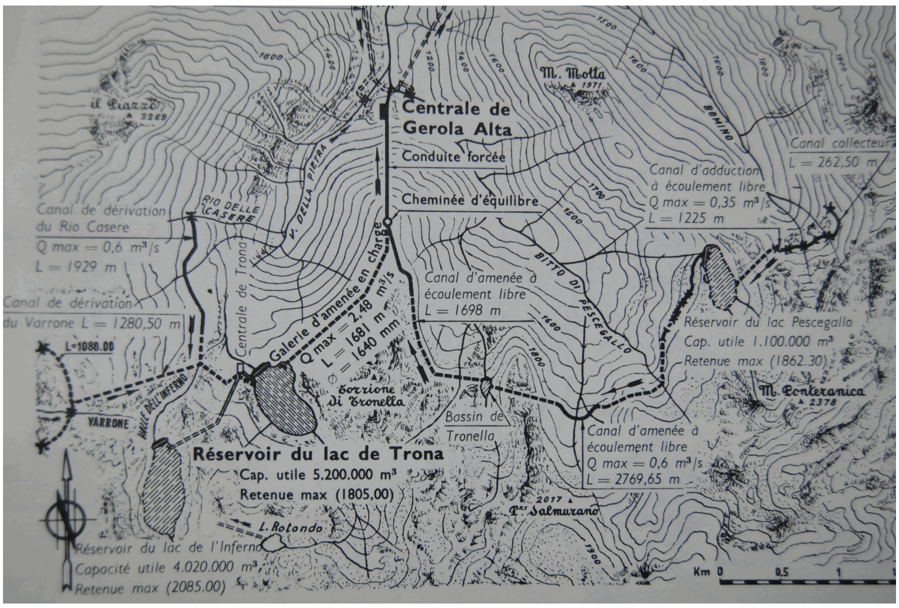
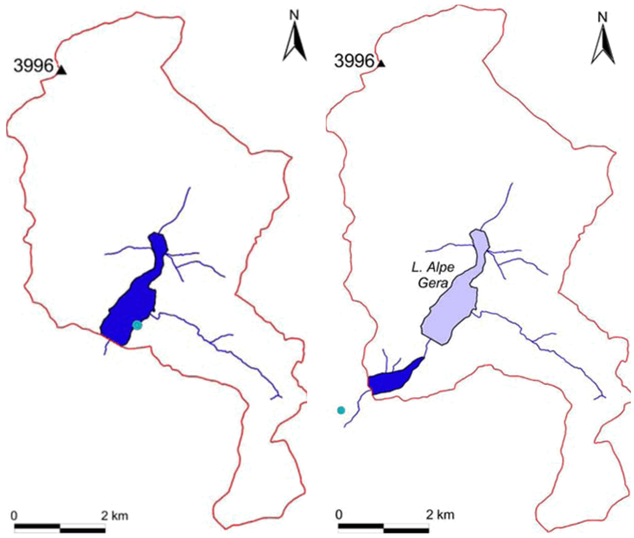


Figure 2.13: Schematic of the hydraulic network of Enel (Gerola Alta power plant)



(a) Lake Alpe Gera **(b)** Lake Campo Moro

Figure 2.14: Watersheds of the smaller lakes of the Enel network

Lake Pescegallo
The lake Pescegallo is located a few kilometres north-east from the lake Inferno. With a storage of only 1.1 Mm^3 is considered one of the smallest lakes, and it is located at an altitude of 1863 meters above sea level. The catchment area, equal to 0.93 Km^2 , is slightly smaller than the connected basin, equal to 0.96 Km^2 . Its waters, together with those of Lake Trona, provide the mechanical energy necessary to the power plant of Gerola Alta.

Lake Trona
Lake Trona is located in a valley to the north of Pizzo Tre Signori (2554 m.) and it was a natural lake of glacial origin until the construction of a large dam has greatly increased the capacity up to 5.35 Mm^3 . It has a catchment area of 2.62 Km^2 and a connected basin of 11.5 km^2 , of which also include the lake Inferno. (Figure 2.15) Its effluent is the torrent Bitto di Gerola.

2.3.4 *Summary*

In this section have been reported, in the table, the data of the lakes used in the project and explained in the previous section.

As already mentioned, the catchment area of Lake Como isn't totally in the Lombard territory; in fact some portions of the basin are in the Helvetic territory, so the data of this lakes were not available for the study. Some reservoirs and release data of some hydroelectric reservoirs were not available anyway, even though the lake is located in Italian territory.

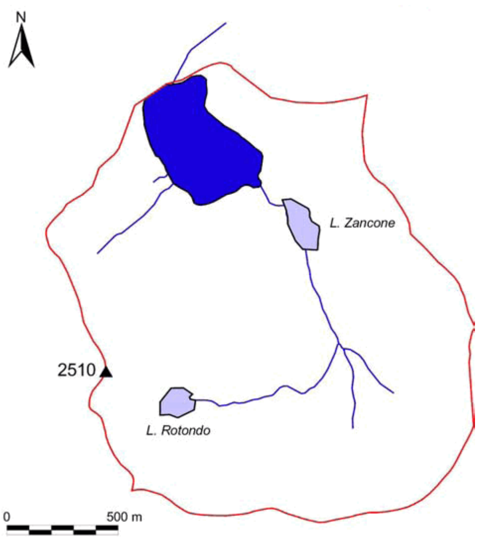


Figure 2.15: Catchment area of Lake Trona

Therefore, it is drawn the Table 2.2, which contains the data of the reservoirs that would be taken into account during the work, but that hasn't had a chance to be used.

The White lake, the lake of Poschiavo and the Alpe Albigna are in the Swiss territory, and therefore we don't have the data of the spatial SWE provided by ARPA Lombardia. The data of dams releases and storages of the lake Pirola and the lake Palu were not available, even if this two lakes are in the Lombardy region.

In Table 2.1 are reported the lakes with available data for subsequent analysis. Subdivisions by operator are also reported, even if not specifically indicated (if necessary, compare the section 2.3.3).

The reservoirs that are placed in succession on the same fluvial rod, and very close to each other, have an indication of the value of the common catchment area and connected basin. In this way, the closing section is intended as the point of the dam placed downhill; the river basin of upstream water body will therefore be part of the catchment area of the basin downstream. The value of the connected basin will be a sum of connected watersheds to each reservoirs.

Table 2.1: Mountain reservoirs features

Reservoir	Useful storage (Mm^3)	Subtended basin (Km^2)	Connected basin (Km^2)	Dam altitude (m.a.s.l.)
San Giacomo	64.0	18.7	322.3	1952
Cancano	124.0	36.0		1902
Montespluga	32.6	24.0	2.9	1904
Truzzo	20.0	10.0	5.5	2088
Belvisio	50.1	27.3	20.1	1486
Venina	11.2	8.3	11.8	1824
Scais	9.1	17.8	34.9	1946
Publino	5.2	1.9	0.5	2135
Mezzo	0.5	1.9	1.6	1936
Santo Stefano	0.6			1850
Alpe Gera	68.1	39.9	50.9	2128
Campo Moro	10.8			1969
Inferno	4.2	1.1	0.3	2088
Trona	5.4	2.6	11.5	1805
Pescegallo	1.1	0.9	1.0	1863
Total	406.9	190.39	463.25	

Table 2.2: Unused reservoir

Reservoir	Useful storage (Mm^3)	Subtended and connected basin (Km^2)	Dam altitude (m.a.s.l.)
White lake	18.0	11.1	2155
Poschiavo	15.8	195.9	962
Pirola	1.9	1.2	2283
Palù	1.8	3.2	1921
Alpe Albigna	70.6	42.3	2040
Total	108.1	253.7	

3 CANDIDATE POLICY INPUTS

The snow data is key parameter of this study. In this chapter we will first see the technologies that are able to provide this type of data, then we will see the methodology followed by Arpa Lombardia to estimate the snow water equivalent. This data will be used as substitute for the usual snow height.[16]

3.1 SYSTEMS FOR MEASURING SNOW HEIGHT

3.1.1 *Measuring precipitation: "snow gauges"*

The snow gauges are usually rain gauges whose changes are made to enable the proper functioning in the most extreme locations. These changes include an antifreeze system, due to the low temperatures at which the snow gauge shall be subjected, a suppressor of evaporation to prevent the loss of water, and sometimes also an anti-wind system, so that the data is not influenced by the greater or lesser interception due to the force of the wind itself. The placement within the landscape context is also important and should be as representative as possible.[11, 13]

There are two types of snow gauges: those manual and automatic ones. The manual snow gauges are made only by the apparatus described above and should be periodically and manually monitored, measured and emptied.

Those automatic, instead, are composed of a data recording apparatus and also of a water collection tank. [12] This way the data is recorded while the melted snow is sent into the collection tank; the capacity of the tank and/or the amount of snowfall, provides the time between two visit in order to empty the tank.

3.1.2 *Manual measurements of snow height*

The most widely used method for the calculation of the snow height is the use of a graduated rod, which is inserted into the snowpack. The problem of this method is the difficult measurement of a single snowfall.

This problem can be overcome through the use of square boards, usually of plywood or lightweight metal, white coloured to avoid as much as possible snowmelt. These boards are placed above the snowpack, or on the ground, and after a snowfall, is measured the

Figure 3.1: Snow gauge of the Waterloo University, Ontario, Canada (a) and a hotplate snow gauge (b)

height of the snow; the table is then cleaned and replaced on the surface.

3.1.3 *Acoustic systems, light transmission systems and heated plates*

There are systems that exploit the reflectivity of snow to acoustic pulses to be able to measure the height. These systems are composed of a sensor, located at a given height, that beeps down. It measures the time the signal takes to reach the surface of the snow and return. The air temperature must be also measured since the sound speed propagation depends on it.

Other systems, instead, measure the variation of the transmission of a light beam crossing the falling snow. These are instruments that provide detailed data on the rate of precipitation of snow and can operate non-stop for a long time, but have the disadvantage that they provide a precipitation rate and not the height of snow.

The third system is composed of two heated plates maintained at the same temperature. During a heavy snowfall upper plate will suffer more cooling due to the deposition of snow on the dish itself and the subsequent melting and evaporation. This plate will need more energy to maintain the same temperature and the energy difference between the two plates is proportional to the rate of snowfall. Even in this case, the device provides the rate of the snowfall and not the height of the snow.

3.2 DIRECT MEASURE OF SWE

There are some methodologies of measurement that allow us to measure directly the snow water equivalent without the measurements of height and density of the snow.

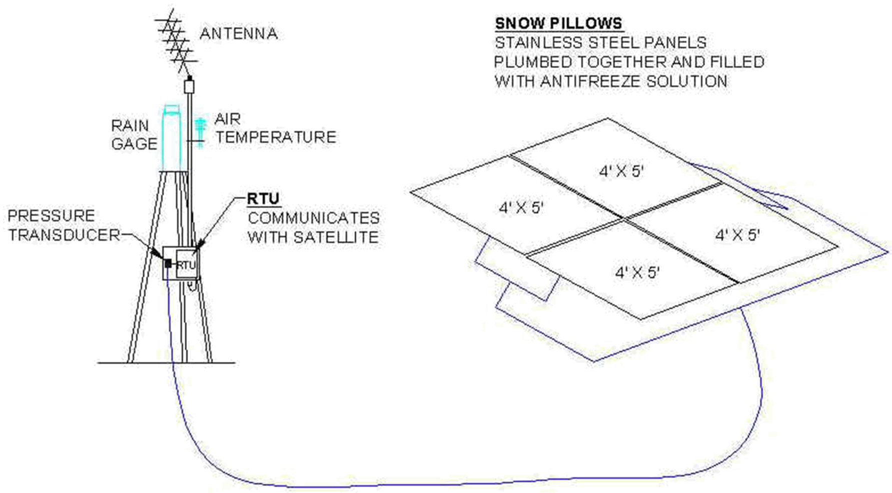


Figure 3.2: Snowpack telemetry system using snow pillow

3.2.1 *Snow core*

One method involves the use a graduated tube with one end shaped to penetrate inside the snowpack. Once inserted the tube down to the ground below, is extracted a core of snow that is weighed on a balance previously calibrated, so that it provides direct measure of snow water equivalent.

3.2.2 *Snow Pillow*

The scheme in Figure 3.2 shows the Snowpack Telemetry system (snowtel) which consists, among other things, of a snow pillow. [11] This is made up of four squares of stainless steel or synthetic rubber that contain, within them, an antifreeze liquid.

The snow, deposited above these squares, applies a pressure on the antifreeze liquid that is measured by a pressure transducer, as in the case in the figure, or by the level of a fluid inside a tube.

In practice, it is a tool that directly converts the weight of snow in snow water equivalent measures.

As shown in Figure 3.2, this is an automatic method because the signal received by the transducer can be transmitted via radio signal.

This system has only one defect: the space required for its installation must be sufficiently wide to allow the "pillows" placement. The location of this tool is very important and it should be done in a location representative of the study area, and without too many disturbances arising, for example, by trees placed nearby or by canyons in the mountains, that promote strong winds.

3.3 ESTIMATION OF SWE BY ARPA LOMBARDIA

In this chapter is presented the methodology for estimation of SWE on mountain watersheds of Lombardy, one of the information included in the hydrological bulletin published weekly by ARPA Lombardia.

3.3.1 *Introduction*

Since 2004, the Lombardy Region has transferred to ARPA Lombardia skills and infrastructure of the former SIMN (Hydro-Tidal National Service), which include, among other things, the quantitative monitoring of water bodies surface. The intensification over recent years of episodes of water crisis has given a further stimulation to deepen and strengthen the methodologies for monitoring the availability of water resources. The occurrence of situations of water stress due to lack of rainfall may in fact generate conflicts between different uses of water resources, that may be difficult to resolve. Is therefore a need for rapid and efficient methods of estimation of the different components of the hydrological balance and, in particular, the water stored in the form of snow that in the basins of the Alpine area assumes significant importance. The methodology developed in the ARPA Lombardia by the Laboratory of Remote Sensing and by the hydrographyc Unit, integrates the analysis of MODIS images with the data from the automated stations network and manual measurement of the snow carried out by technicians of the Avalanche Center in Bormio. [2]

3.3.2 *The methodology*

The estimates of SWE using the following methodology are based on a simplified model that takes into consideration just the new accumulation of snow and the eventual melting, with time rate of seven days.[18, 4, 25] The numerous simplifications introduced in the variables involved and in the treatment of complex phenomena such as accumulation, melting, densification of snow, are justified by Arpa as necessary to be able to provide the estimates for a large portion of the territory on a regular basis, and following a repeatable methodology, with a view of the support of the decisions.

3.3.2.1 *Punctual estimation of SWE*

The first important step of this methodology is the acquisition of data resulting from nivometeorological stations. These can be automatic or manual. From manual stations is obtained directly the measurement of variation of SWE through measurements of density and height of the snow; from the automatic ones, instead, measure of the height of the snow are made by various methods (see section 3.1) and it is important the daily average temperature. The total number of stations used in the winter season 2005-2006, after deleting some points of measurement unreliable or too discontinuous in time, was 25, including 12 manual stations and 13 automatic.

In addition to automatic and manual stations mentioned above are added some special surveys (called "itineraries") carried out by operators of the Avalanche Center in Bormio for estimating the risk of avalanche. These surveys are also useful to validate the estimates of SWE because they include detailed measurements of the thickness and density of each layer of the snowpack. In addition, these surveys are often carried out from medium to high altitude and also come in the spring.

Through the hypothesis that the snow density is constant and equal to $108 Kg/m^3$ (for the fresh snow), it is possible to estimate the accumulation of new SWE while, using the knowledge of the temperature, can be calculated the rate of melting of the snow through a model *degree day*.

$$\text{Fresh snow} \qquad \Delta SWE_n^+ = \sum_i \rho_i h_i$$

$$\text{melting} \qquad \Delta SWE_n^- = -c \sum_j (T_j - T_0)$$

where ρ_i is the snow density and h_i is the i-th snowfall thickness occurred during the n-th weeks; T_j is the average daily temperature of the j-th days , T_0 is the melting temperature (take equal to 0°C) and c is the melt constant of the model *degree day*.

Through these two formulas, it is possible to calculate the value of SWE on a weekly basis, depending on the value of SWE calculated the previous week:

$$SWE_n = SWE_{n-1} + \Delta SWE_n^+ - \Delta SWE_n^-$$

Using a digital terrain model (DTM) The punctual estimation thus obtained are spatialized on a regular grid with a pitch of 100m through linear relationships with altitude using a digital terrain model (DTM). These relationships have been calibrated on four different areas of Lombardy on the basis of homogeneous weather and climatic features: Alta Valtellina, Val Malenco - Chiavenna, Adamello, Orobie - Prealpi.

3.3.2.2 *MODIS images*

The satellite data used to have snow maps are satellite images derived from MODIS sensor, mounted on NASA's Earth satellite, which provide information in the spectral bands of red, near infrared and middle infrared, the latter needed to discriminate snow from the clouds.[20]

The MODIS maps must be re-projected into the Gauss Boaga - Rome 40 reference system and must be reclassified by an Unsupervised ISODATA algorithm, into three classes: snowy pixel, not snowy pixel, no-date. The image that has pixels with no data, usually as a result of land cover by clouds, is classified again by the images of the next few days. This is possible because the MODIS data is daily while the processed and transmitted data by ARPA is weekly.

The resolution of these images is 500 meters to the ground, not so high but it is the only one that allows to obtain information in the mid-infrared, which, as said before, is necessary for the discrimination of the snow.

The maps thus obtained are used as masks to eliminate from the maps of spatialized SWE all pixels that are not covered with snow.The snow maps are moreover combined with Digital Terrain Model to build the depletion curves that describe the evolution of snow cover percentage of the different altitudinal belts.

Specific experiment was conducted to evaluate the importance of the contribution of satellite-derived maps of snow in the estimation of SWE. For some significant dates was calculated the potential SWE on river basins with and without the use of maps of snow. In the absence of the maps of snow the overestimation of SWE in a relatively small basin and at medium-low altitudes would be marked, like the portion of the Adda basin on the lake of Como. In the pre-lake portion of the Adda basin or in the Oglio basin (wider and at higher altitudes) major errors occur in the spring, where the rapid disappearance of snow on the ground is well identified from satellite images.

3.3.3 *Verification and Validation [2]*

The verification and validation of the produced estimates of SWE were carried out at different levels:

- verification of submodels (of accumulation and melting) through comparisons with independent measured values;
- validations of the local estimates of SWE at meteorological stations, by comparison with independent direct measurements carried out in proximity of the stations;
- comparisons between the estimates of SWE at the level of small reservoirs such as Lake Barbellino (Val Seriana) and storage of

the reservoir and flow turbinate in output (with the help of ENEL SpA);

- assessments of the estimates on large mountain watersheds, by comparison with independent indicators (e.g., the "snow index" of the Consortium Adda).

3.3.4 *The application of the methodology*

The final result of Arpa, as regards the estimated data of SWE, is slightly different from that stated so far. The first part of the estimate is exactly as described in the previous paragraphs. They use the information resulting from snow and weather stations to estimate the accumulation and melting snow to provide the data of SWE. At the same time, however, data of density of the snow and temperatures at various altitudes are used, provided by Enel. These data are recorded during some campaigns that the company carries out in the mountains monthly or biweekly during the winter and spring. With this data, which have a greater level of detail than those held previously, and with the knowledge of the height of snow,can be made a second estimation of SWE.

The final data will therefore be the average of the two results obtained, spatialized through the use of the DTM on regular grid of 100x100 meters and cropped with the masks resulting from processing of the MODIS images.

3.4 AREAL SUBDIVISION

For this part of the project was necessary to define some sub-basins of the Adda river. Then it was possible to assess whether the SWE, or its melting, subtended only to the considered mountain watersheds, was sufficient to define a sort of effective SWE. This SWE was designed as the part of the melting snow that is not captured directly from the mountain reservoirs and then immediately makes available its dissolution in Lake Como. The full methodology and the results obtained are shown in Section 3.7.

A further division of the territory was made according to the Thiessen polygons, in order to have an estimation of the areal precipitation.

3.4.1 *The mountain watersheds*

Starting from the DEM (Digital Elevation Model), i.e. from the heights of the digital model of the Lombardy Region terrain, with a pitch of 100 meters, it was rebuilt the hydrographic network (Figure 3.3). This was possible using the model ***Deterministic 8***, implemented in the hydrological analysis modules of the program Saga-GIS.

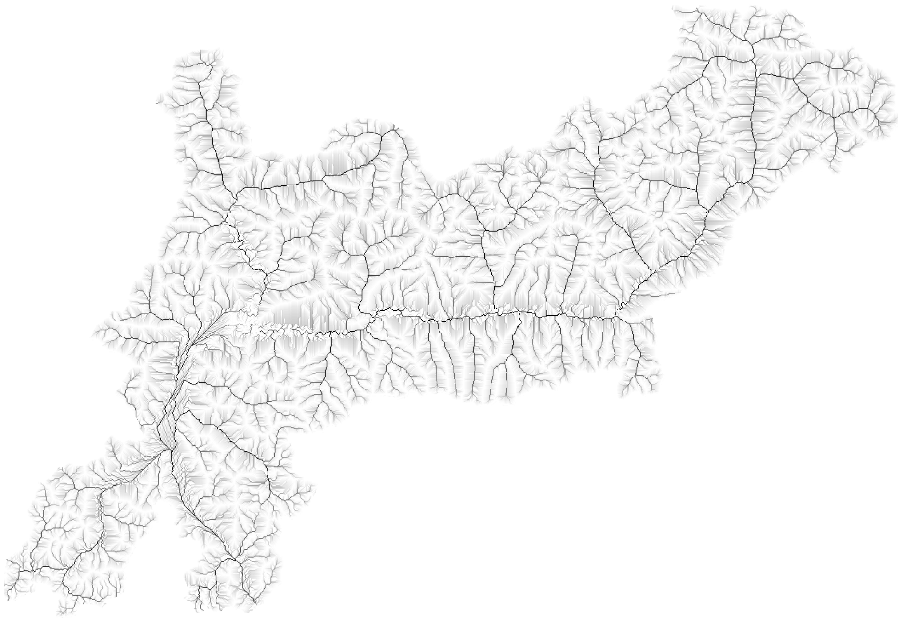


Figure 3.3: Reconstruction of drainage network

This model requires that the water present in a cell can move in the direction of the neighbouring cell with a greater slope. We have, for each cell, the eight possible flow directions (hence the model name). It determines the greater slope of each cell with its neighbours through a formula that takes into account the heights of the cells and the distance between the centres of each cells.[17]

This method has strong limitations on use as it is not suitable for flat or slightly hanging terrain because the eight directions aren't enough to correctly describe the phenomenon. In this case this problem is not almost observed because the territory is mostly mountainous.

To obtain a network of canals from the model, a threshold value has to be set, which will be used as the minimum value to select the cells that will be part of the network. If the value is too low, the determination of the channels in the early parts of the runoff can bring mistakes, because the algorithm will also accept cells with a low value. Increasing this value will be decreasing the error but also the number of channels. There is no universal method for choosing the threshold value because it depends on the accuracy of the DEM and on the morphological and geological examination of the area. So the value was set via trials and errors until a useful result was achieved.

Once having calculated the hydrographic network it was superimposed the layer of hydroelectric reservoirs to obtain, from the meeting downstream point of the lakes with the river network, the closing section that will be used as input to another algorithm, called ***ups-***

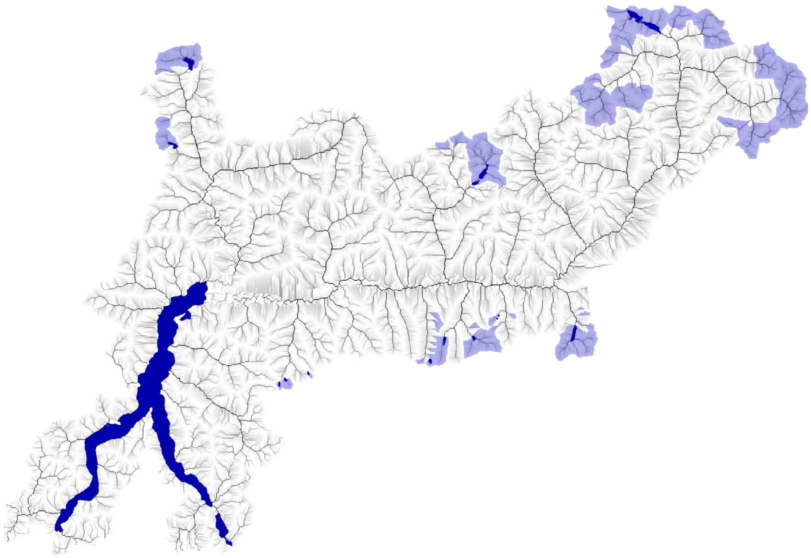


Figure 3.4: Catchments subtended and connected to major hydroelectric reservoirs

lope area. This will help to calculate the subtended catchment areas and the connected basin (using as input the starting point of the intake structure) of each mountain basin because it gives in output the amount of area (and its location) that allows water to flow in the direction of the closing section which was pointed. (Figure 3.4)

3.4.2 *The Thiessen polygons*

Given the nature of the project and the importance of the calculation of SWE, it was necessary to include in the important parameters, also the spatial distribution of rainfall and snowfall.

There are several methods that allow spatial rainfall. It was decided to use the method of Thiessen polygons even if, when applied to a mountainous area like the one examined, produces outputs with a certain degree of error, mainly due to the influence of orography and exposure. It was made this choice due to the speed of implementation of this method and because of the non-uniform presence of nivometeorological stations in the study site.

The method of Thiessen polygons is based on the concept of associating to the points of the region of interest, in which data is not available, the value of the variable in the nearest measuring station. The construction of these polygons is accomplished in two phases. Firstly the points of adjacent stations are joined by a straight line. The next step involves the drawing of the perpendicular lines. The junctions of these seconds lines represent the boundaries of the areas of expertise. To every point in the area of competence, also called topoieta or

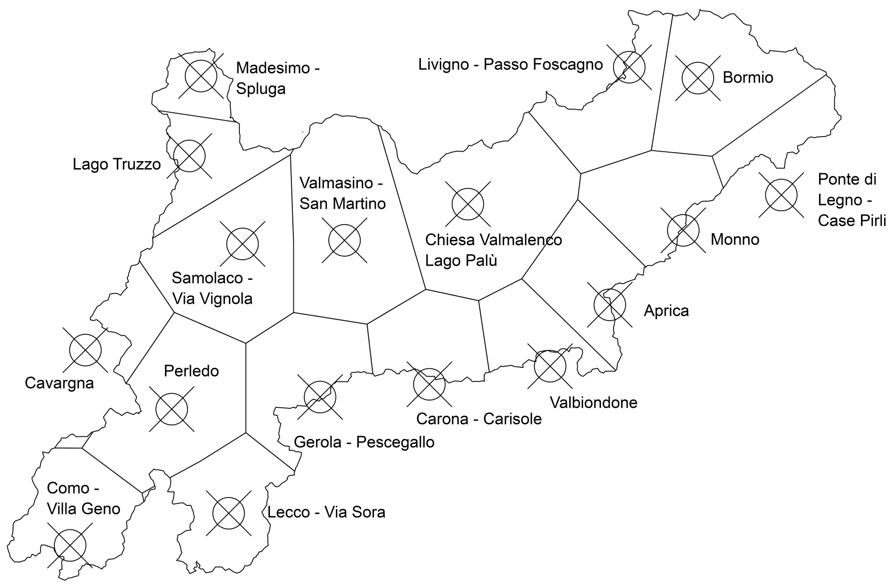


Figure 3.5: Sub-basins divided using Thiessen polygons

Thiessen polygon, is assigned the value of the rain measured in the reference station.

The Figure 3.5 shows the basin of the Adda divided into sub-basins according to the method of Thiessen. The points shown in the figure are the location of the weather stations used for the calculus. [23]

3.5 ANALYSIS OF THE MOUNTAIN HYDROELECTRIC RESERVOIRS

In this section it's made an initial analysis of the available data. In particular, having access to the storage and the release data of hydroelectric reservoirs, day by day, the value of total water inflow can be obtained with the formula:

$$a_{t+1} = S_{t+1} - S_t + R_{t+1}$$

where a corresponds to the inflow that we wanted to calculate, S to the value of the storage and R corresponds to the daily release.

In the second comparison, instead, are considered the values of areal rain calculated by Thiessen polygons. For the snow it was used the value of the temperature recorded in the same meteorological station used for the rain, and it is defined that the daily mean value of temperature below 0°C corresponds to a snowfall.

3.5.1 *The releases*

The time series of historical releases has been analysed graphically, year by year, in order to assess the individual performance. It is then added the average of these values in order to have the overall average performance of the releases of reservoirs over the years. (Figure 3.6)

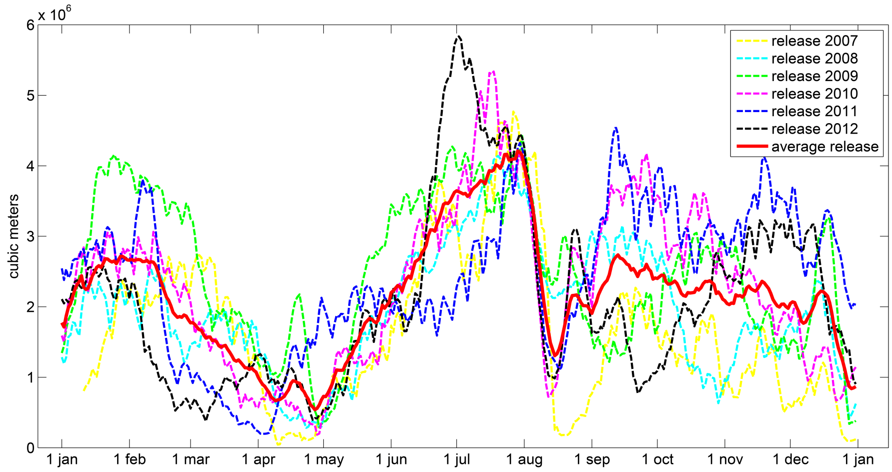


Figure 3.6: Average of the hydroelectric releases

We must remember that, in this plot, are overlaid different release policies because of the different owners of the reservoirs.

From this plot, it can be seen that the maximum release for all reservoirs takes place towards the end of July, almost certainly in correspondence with the highest demand for electricity for the functioning of air conditioners.

All the reservoirs have a minimum release between the end of April and the beginning of May. This happens in correspondence with the lowest storage possessed and at the beginning of the period of the snowmelt because, from this point on, will begin the inflows to the lakes and the filling period.

The period starting from the beginning of September until December is a bit chaotic because it corresponds to the period of the beginning of the precipitation that produces very irregular trends in releases. If these trends will be compared with the trend of precipitation over the same periods, one can notice that the years that have higher releases are the same ones that have the greatest amount of precipitation during that period.

As a further analysis, was performed a heatmap on releases, shown in Figure 3.7, in which you can see how different release policies have been followed over the years, while a high value between late July and early August was maintained. In some years, like 2008, the releases are concentrated in one period while in others, such as the 2010 and 2012, the releases are distributed throughout the year.

As final analysis, the daily average releases of hydroelectric reservoirs, calculated with a three-day moving average, were split for ownership, getting the Figure 3.8. The releases of the reservoirs Cancano and San Giacomo (A2A), are not of particular importance in this comparison. It can be noticed only that these reservoirs have higher values

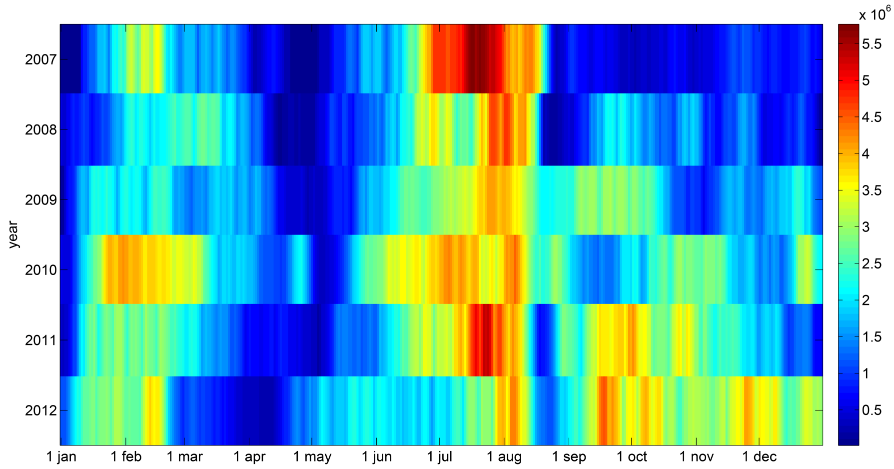


Figure 3.7: Heatmap of releases

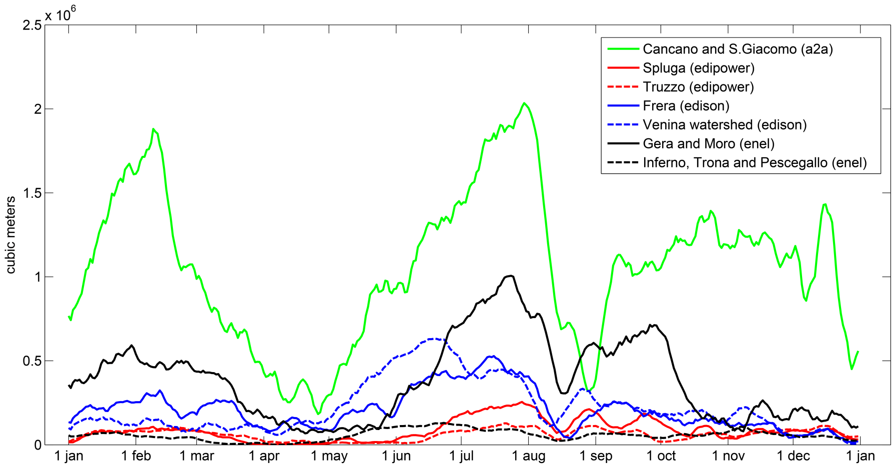


Figure 3.8: Hydropower releases according to handler

of release throughout the year because they are the major reservoirs in the area.

Looking at the releases of Edipower, red lines, it can be seen that the behaviour of the two different reservoirs is, after all, quite similar. This also happens for the releases of Edison, blue lines, even if the peak of the basin of Venina is slightly earlier than the one of the lake Belvisio.

The Enel's behaviour is quite different. The basin of Trona has the releases peak very late in time, nearly a month compared to the Enel's second reservoir. The reservoirs of the lake Alpe Gera and lake Campo Moro undergo a considerable reduction of releases from mid-October, while the basin of Trona is able to maintain the same release value, throughout autumn and winter. This may happen because the two basins are located in very different orographic and climatological areas. The lakes of Gera and Moro are placed in high Valmalenco, and then receive the snowfall before the other reservoirs, which does

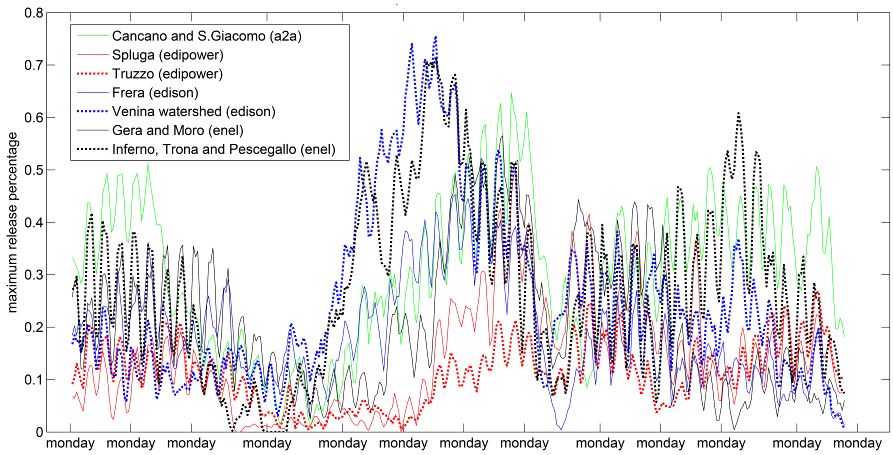


Figure 3.9: Releases normalized to the maximum release

not make available the water content until the next year. The manager is therefore forced to reduce the releases, waiting the snowmelting.

This type of analysis was also performed without weekly mediation to obtain the trend in Figure 3.9, in which it is also normalized the value of each series to the absolute maximum value present in the same series.

From this type of analysis can be first of all noticed the cyclical nature of the releases due to a lower demand for electricity on weekends. Moreover, there is the interests of managers to use less water to keep it available when needed.

As already noted, the minimum release is around April, while the news is the diversification of the peak values. If compared to other reservoirs, the basin of Venina and the one of Trona have the peak anticipated around the middle of June. What seems interesting is that these two reservoirs are the only ones to be south of the horizontal rod of Adda and this suggests that localization influences greatly the management policy.

Taking into account total inflows derived from the storage volumes and releases, and comparing them with the latter, it can be seen the trends in Figure 3.10.

In this figure is clearly visible the annual cycle of reservoirs inflows and how the winter period, around December, is the least experienced value of inflow. This is because during this period the precipitation is snowy and the cold temperature do not allow liquid water to reach reservoirs.

3.5.2 *The reservoirs*

The series of reservoirs was analysed dividing them between ownership to quickly identify those operators who have at their disposal the largest volume of water. (Figure 3.11)

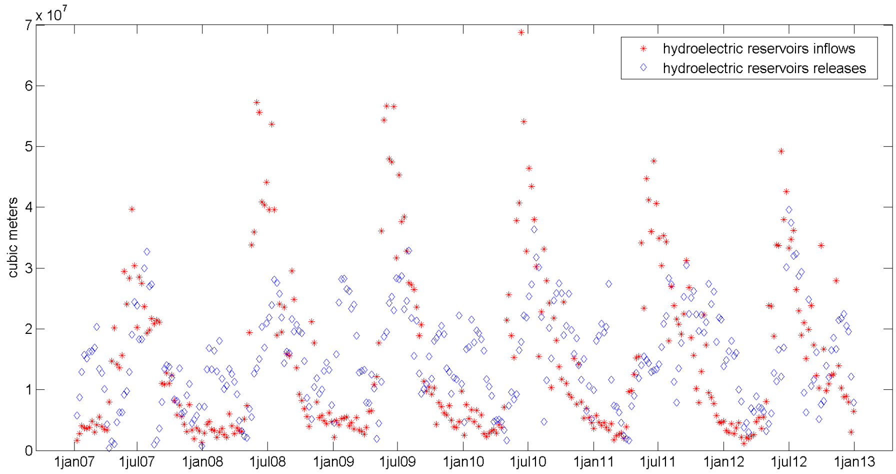


Figure 3.10: Direct comparison between releases and reservoirs inflows

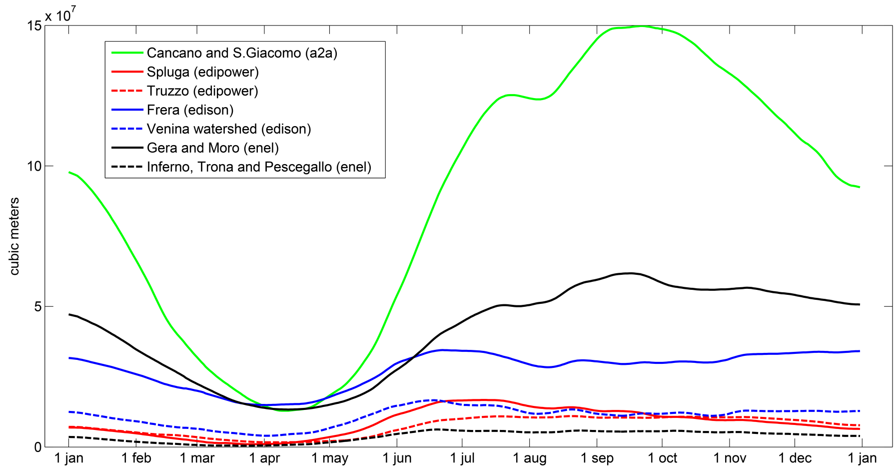


Figure 3.11: Storages of hydroelectric reservoirs divided by ownership

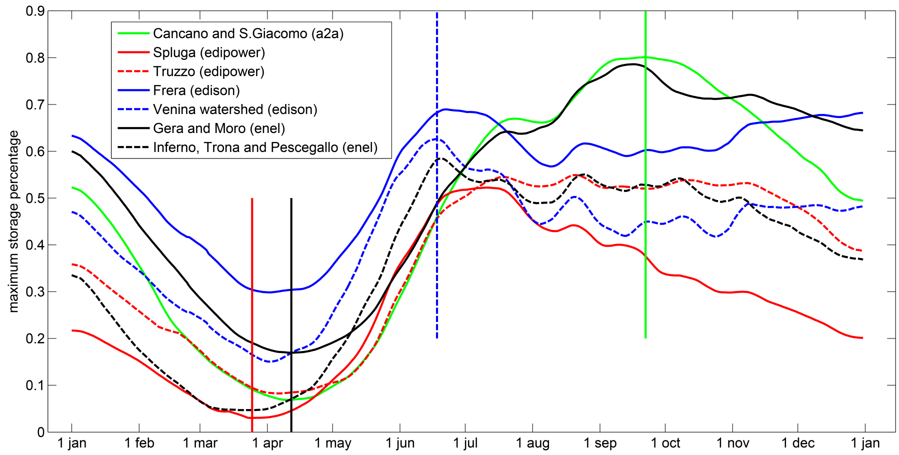


Figure 3.12: Normalized hydroelectric reservoirs

In this image we can see the prevalence of the reservoirs Cancano and San Giacomo and the fact that Edipower is the operator with less available storage. To get a better idea of the trends of individual reservoirs, the series are been normalized according to the maximum storage resulting from the plot in Figure 3.12.

The first two vertical lines indicate the first and the last value of the minimum storage. The colors and shape of the lines recall the single reservoir, so it can be identify. In this case the first basin that reaches the minimum storage value is the lake Spluga. The little difference of time between the first and the last minimum value indicates that all the lakes reach it at the same time, around the beginning of April. The second two vertical lines indicate, instead, the first and the last basin that reaches the maximum value of storages. In this case there is a considerable width between the lines, that probably indicates a different timing of snowmelt, a difference of rainfall between the zones or a different management of the resource.

Looking at the trend of the series from August onwards, there is a certain difference in behaviour between the reservoirs along the Adda, which are able to maintain high their own levels, and those located in the basin of Mera, especially lake Spluga, which performs a real cycle of storaging and releasing. An explanation of this fact can be found in the lack of rain in this basin.

Looking at the trend of the lake Cancano and San Giacomo, it will notice a significant increase in storage followed by a sudden drop in autumn. Rains are very abundant in this basin and allow it to maintain high levels of the lakes until the rainfall become snow. It happens before the other reservoirs because they are placed at high altitude.

The basin of Lake Belvisio has a completely different behaviour because, at the end of the year, manages to have a second peak of storage.

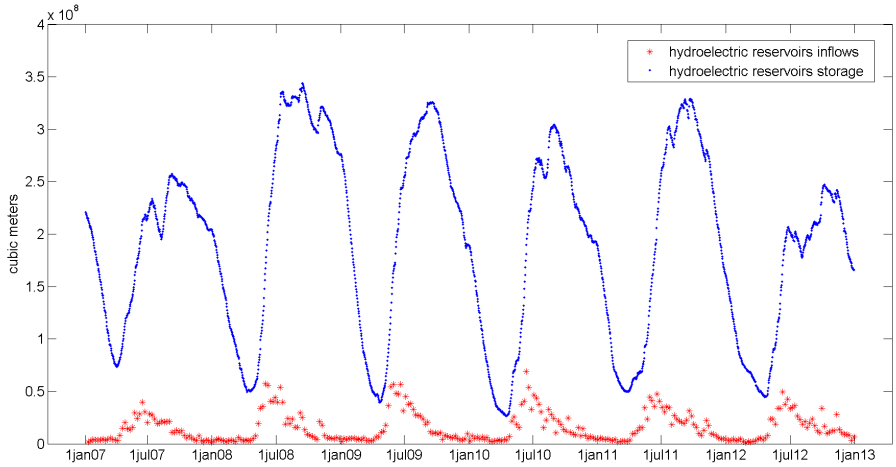


Figure 3.13: Comparison between storage and inflows of reservoirs

The behaviour of Edipower reservoirs is strange because is hard to understand if the controllers don't wont to exceed 50% of the maximum storage or they aren't able to.

Now we recall the chaotic behaviour of the releases in the autumn and winter period. In this case the reservoirs don't follow the same trend. The Alpine reservoirs, in fact, are placed at different heights and are greatly affected by the difference in precipitation that may fall within their territory. A lake place further downstream will continue to have rainfall and then will be able to release more water while one, place at a higher altitude, will begin to have snowfall before the others, so water will be not immediately available in the reservoir.

The comparison of the reservoirs with the related inflows suggests not so many details. The only thing that shines through Figure 3.13 is that the maximum value of inflow, as expected, is detected shortly after the minimum value of storage.

3.6 ANALYSIS OF SWE DATA

Let's finally introduce the snow data.

As first thing, it is need to remember that the snow information calculated by Arpa, and then at our disposal, is a weekly data. So in the next plots will be represent this type of data.

In the Figure 3.14 was compared the weekly SWE data with the storage volumes in all considered reservoirs. The first thing that is noticed is that the peaks of storage and SWE are diametrically opposed during the year, a situation consistent with the fact that when there is accumulation of SWE there is a small inflow to the lakes and occurs the release for the production of energy is needed; vice versa, when takes place the melting of snow, and so when there is a reduc-

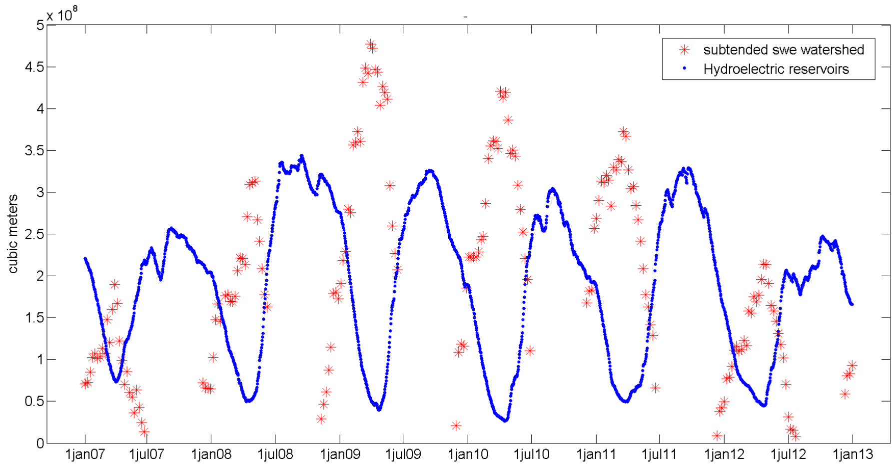


Figure 3.14: SWE comparison with the storage

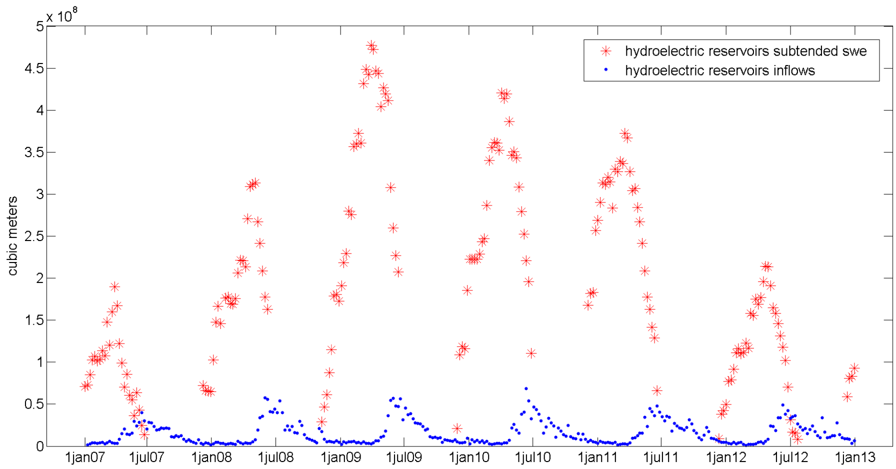


Figure 3.15: SWE comparison with inflows

tion of SWE, the inflow to the lakes is maximum, and the reservoirs have an increasing value of storage.

There is a second consideration to made. When there is not so much swe, there are a low levels of water in the storages. But when there is a considerable amount of snow, the volumes in the reservoirs aren't as high as levels of the swe because the reservoirs have a maximum storage values. Therefore, reservoirs are not able to collect the entire snowmelt and a part of it is forced to release immediately. This premise is at the basis of the considerations that will be made later, regarding the concept of effective SWE. (Compare the paragraph 3.7 of this chapter)

As we said earlier, the maximum inflow in the hydroelectric reservoirs occurs during the period of snowmelt. Even if the two time series have differences of an order of magnitude, the results are correct because the inflows are produced by the melting of swe and not by swe directly. (Figure 3.16)

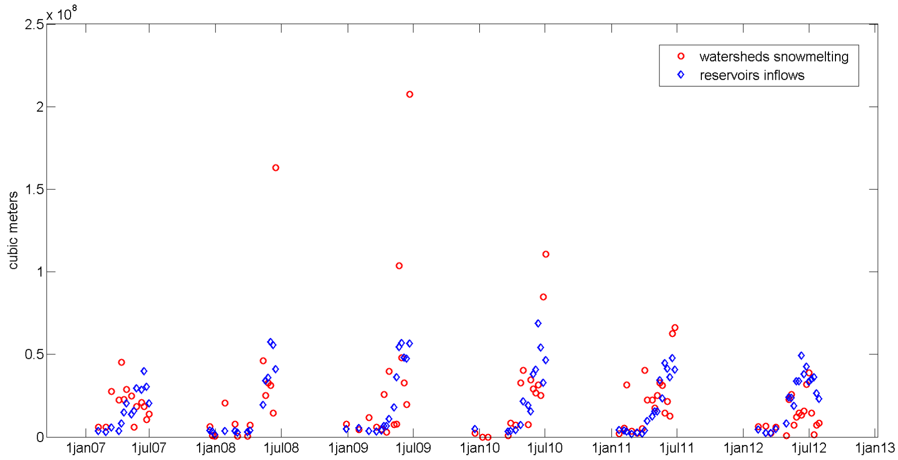


Figure 3.16: melted SWE comparison with inflows

For the creation of this comparison were taken into account only the inflows to the lakes corresponding to a week in which the snowmelt has occurred.

In this way, the plot is even more clear even if there is a certain difference between the results. The points with more snowmelt than inflow can be explained as follows: the trend of ground surface is the only taken into account for the creation of drainage basins. In this way the underground geology of the area is not taken into account. Therefore it is possible that a part of the water infiltrates into the ground and follows different paths that can't bring it into the reservoirs.

The last comparison, performed to check the consistency and correctness of the available data, was to create an annual integral of the data itself. The result is shown in Figure 3.17. Even in this case the trend of the inflows was calculated only when the respective snowmelt was present in the same week.

The proper trend would provide the snowmelt bars, the blue ones, always higher that the inflows bars, due to the infiltration that we have just mentioned. The fact that this doesn't happen in 2008 and that in the period between 2011 and 2012 there is a convergence of the points, allows you to guess the lack of some data that are important for the proper comparison with inflows, i.e. that the snowmelt alone is not enough to explain the trend of inflows in reservoirs.

Therefore the snowfall in the study area has been added to integrate this lack of information.

From Figure 3.18 can be seen how the contribution of precipitation is certainly not negligible compared to the snowmelt.

Than, it has been calculated the annual integral using these data and the results are shown in Figure 3.19.

The blue bars represent the sum of the rainfall precipitation and snowmelt during the course of each year. The green bars represent the sum of the annual inflows only in the weeks in which there was

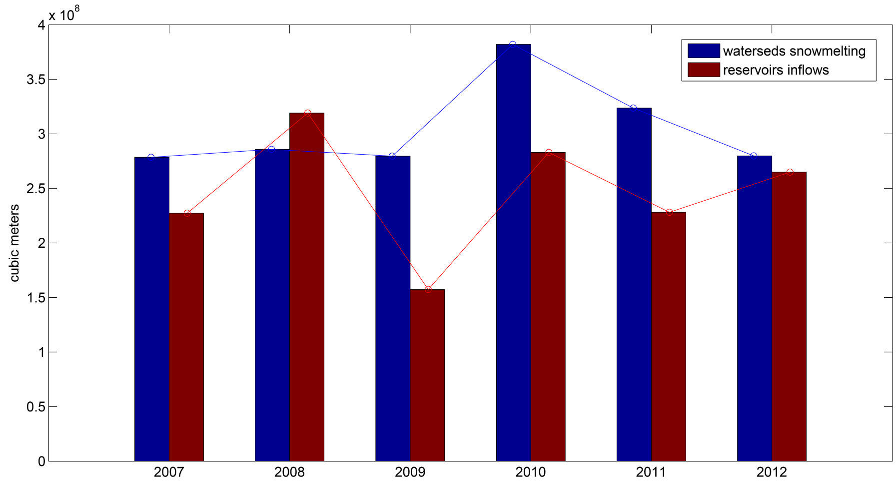


Figure 3.17: Snowmelt annual integral

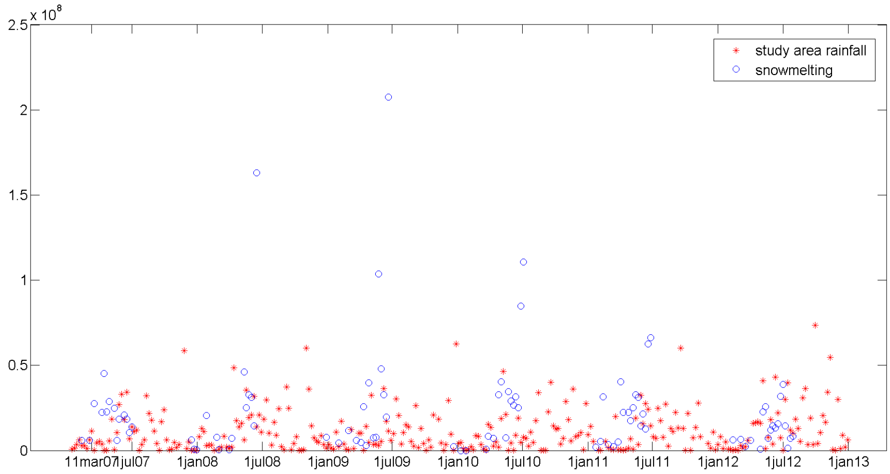


Figure 3.18: Comparison between snowmelt and basin-mediated rainfall

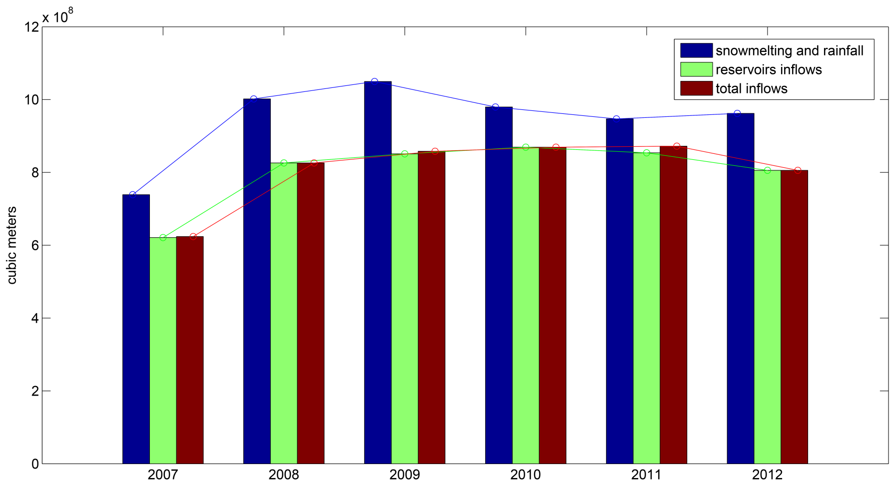


Figure 3.19: Annual integral of the snowmelt with rainfall

at least one of the variables between snowmelt and precipitation. The red bars represent the total amount of inflows over the years.

There are still some minor differences that can be justified with the great number of simplifications that have been made. First of all the calculation of SWE, but also the methodology of rainfall spatialization over such a vast and orographic different area, and the lack of some important data during certain periods due to the malfunctioning of some snow and meteorological stations.

3.7 EFFECTIVE SWE

As we mentioned in the paragraph 3.6 and looking the Figure 3.14, the SWE peak, in some cases, corresponds approximately to the values of the peaks of storage. In other cases, when the SWE peak was greater, the maximum storage results practically constant in time and with a less value than the maximum of SWE. This is due to the fact that the hydroelectric reservoirs have a maximum volumetric capacity and, therefore, it may happens that the reservoirs are not able to contain all the SWE present in their catchment areas. To assess the possibility of this feature, it was decided to introduce a variable defined as effective SWE.

3.7.1 *The calculation methodology*

In the first place, the basin is divided into two sub-basins defined as "free" and "connected", to which correspond the respective values of SWE. Like the name suggests, "connected" basins is formed by the sum of the catchment areas of individual hydroelectric reservoirs while "free" basin is the remaining part of the territory.

For each reservoir was calculated the difference between the maximum volumetric capacity and the effective storage possessed every day.

$$V_{t_{residual}} = V_{MAX} - V_t$$

This factor is the maximum amount of water that the considered reservoir is able to contain in case the SWE completely melts. The excess part have to be released immediately from the reservoir.

The effective SWE is just the difference between the SWE present in the catchment area and the highest remaining capacity of that day.

$$SWE_{effective} = SWE_t - V_{t_{residual}}$$

If there is a positive difference, the effective SWE exists and the surplus part of the melting is released downstream. If negative, the reservoir is completely able to contain the total melting of the SWE.

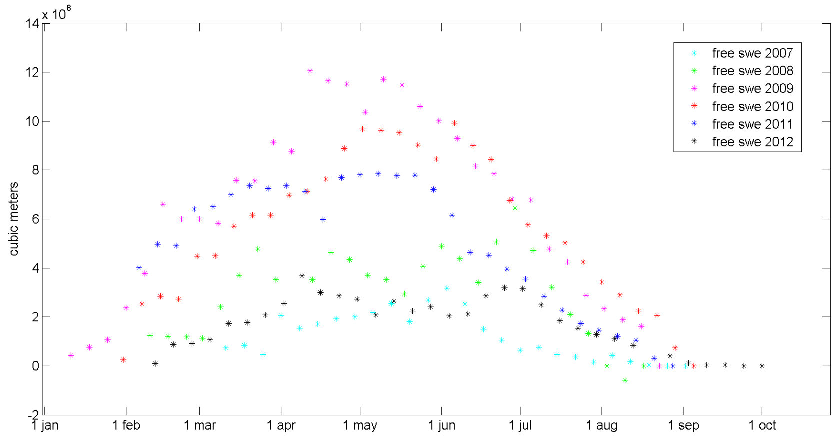


Figure 3.20: Annual trend of free SWE

3.7.2 *The results*

In Figure 3.20 is represented the trend of "free" SWE over the years. This particular parameter represents the amount of water that surely will reach the lake Como without being intercepted by alpine hydropower reservoirs and it is definitely an important parameter to know.

In Figure 3.21 is represented, instead, the trend of effective SWE defined before. To be a good control parameter, it should have trends that, at least the beginning of the year, are positive for all reservoirs, in order to have an amount of water that escapes the control of the dams and then immediately flows into the lake Como.

However, it must be remembered that the swe data are available only for a limited time. The same type of above analysis, carried out over a longer period of time, could achieve positive results and then proves the correctness of this methodology.

Unfortunately it doesn't happen except in some years and in certain reservoirs, especially those with greater capacity. Therefore, this parameter isn't interesting for our analysis and will not be taken into account.

3.8 CONCLUSION

After all these analyses, was drawn up a list of parameters that will be used as candidates for the selection of data that can better explain the performance of the controls of Lake Como.

All data have been weekly grouped to be consistent with the data of SWE, that was more slack.

- **release** of mountain hydroelectric reservoir
- **free SWE**, calculated as in Section 3.7.1

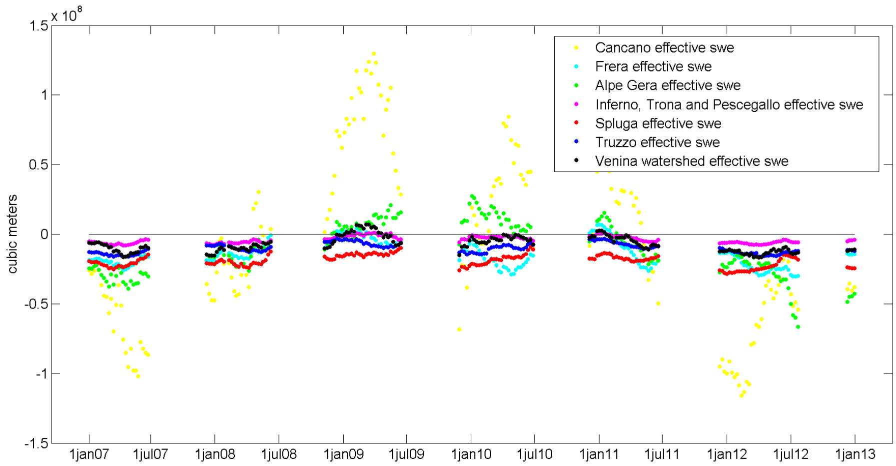


Figure 3.21: Effective SWE trend

- **total SWE**, i.e. the SWE over all the basins above lake Como (Adda and Mera)
- **free melting** of SWE over the "free" sub-basin
- **total melting** of SWE over the study area
- **inflow** to the considered mountain reservoir
- **release + free SWE**, i.e. the sum of weekly releases and the free SWE
- **release + free melting**, i.e. the sum of weekly releases and the melting of the free SWE
- **precipitation** over the study area
- **rainfall** over the study area
- **freezing point trend** in function of the height

For this last parameter we have used data derived from weather stations that have provided the values of precipitation. It was then used a linear interpolation with the height, in order to identify the altitude where there is the freezing point of the day. The results are shown in Figure 3.22.

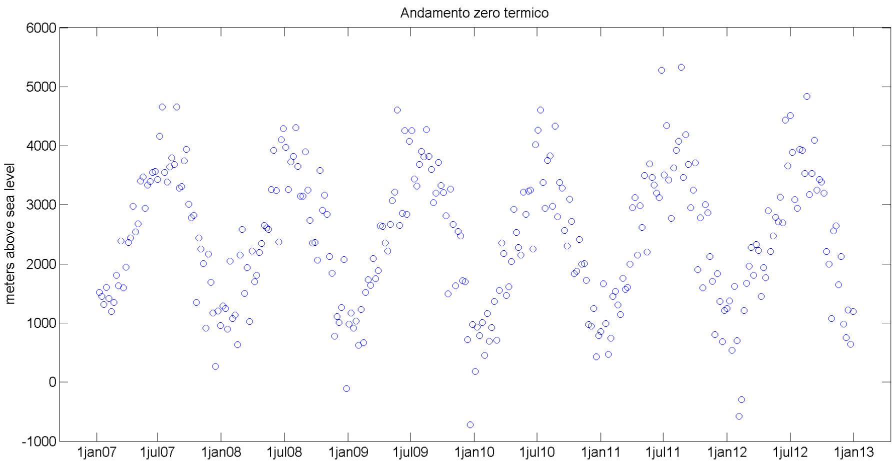


Figure 3.22: Weekly trend of freezing points

4 OPERATING POLICY

The first part of the chapter provides the definition of Pareto efficiency and the description of the methods to obtain it. Subsequently, there is provided a summary of the main methodologies that allow the choice of the optimal solution, and finally the results obtained for the research in question.

4.1 PARETO EFFICIENCY

In the study case it were identified two objectives, the annual average of flooding days and the daily average of irrigation deficit, which should be both minimized and that depend on a single decision: the release from the dam of Olginate.

It is therefore necessary identify the decision u that leads to the best value of the pair of objectives $J^1(u)$ e $J^2(u)$.

This solution is obtained from the value of the objectives J^{1*} e J^{2*}, shown in Figure 4.1 with the letter U, and this is called "utopia point". This point is so named because it is obtained by minimization of one objective at a time, and therefore can't be achieved if the objectives are conflicting, such in this case. [10]

It is therefore necessary to look for other solutions. To determine which are the best we need to introduce two definitions:

- A solution u' is said *dominant* on a solution u'' if the first improves performance compared to all objectives, i.e. if:

$$J^i(u') < J^i(u'') \quad \forall i$$

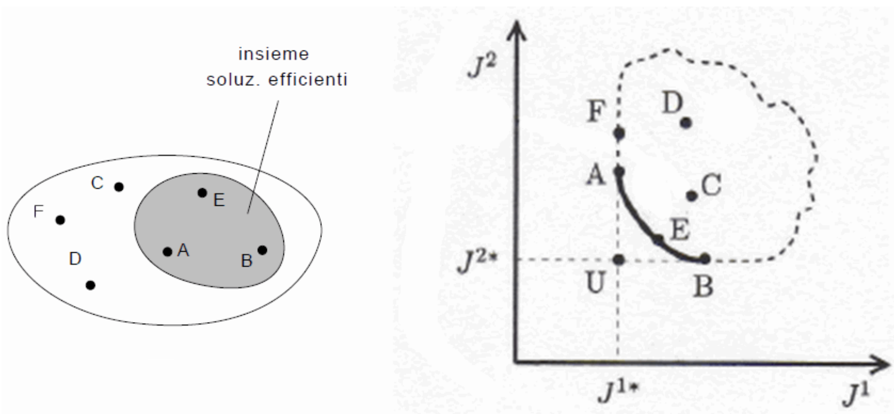


Figure 4.1: Pareto frontier in the space of objectives

- A solution u' is said *semi-dominant* on a solution u'' if the first improves performance compared to at least one objective, being equal the other condition, i.e. if:

$$J^i(u') \leqslant J^i(u'') \quad \forall i \qquad \exists k : J^k(u') < J^k(u'')$$

The only solutions to be considered are those for which there is no decision that provides better performance for both goals. These decisions are called *dominant*, or *efficient*, or *Paretian*, as well as the corresponding points in the space of objectives. The other decision are called dominated (if there are other decisions that improve both objectives) or semi-dominated (if there are other decisions that improve one objective without worsening the other). The set of efficient solutions provides the Pareto frontier, as indicated in Figure 4.1 through the line in bold joining the points A and B.

The choice of a solution within the set of efficient solutions is subjective because it is necessary to make a judgement about the relative importance of the various objectives.

4.2 OPTIMIZATION AND SIMULATION

In order to create the Pareto frontier we need to bring the many targets problem to a family of problems with only one objective, each of which can be solved with simpler and known methods.

There are two possibilities: the method of weights and the method of constraints.

The **method of weights** allows the creation of a scalar objective function using the linear combination of the elements of departure.

$$\min_u |J^1(u), \ldots, J^q(u)| \quad \Rightarrow \quad \min_u J(u, \lambda) \quad \forall \lambda$$

being:

$$J(u, \lambda) = \sum_1^q \lambda_i J^i(u) \qquad \text{con} \sum_1^q \lambda_i = 1 \quad \text{e } 0 \leqslant \lambda_i \leqslant 1$$

Set the value of the coefficients λ_i (called weights), the Single-Objective parametric problem can be solved with normal optimization techniques with one goal. The result of optimization provides Pareto-efficient solution of the original Multi-Objective problem. Changing the value of the weights, various efficient solutions can be determined as shown in Figure 4.2.

$$\lambda_1 J^1 + \lambda_2 J^2 = K$$

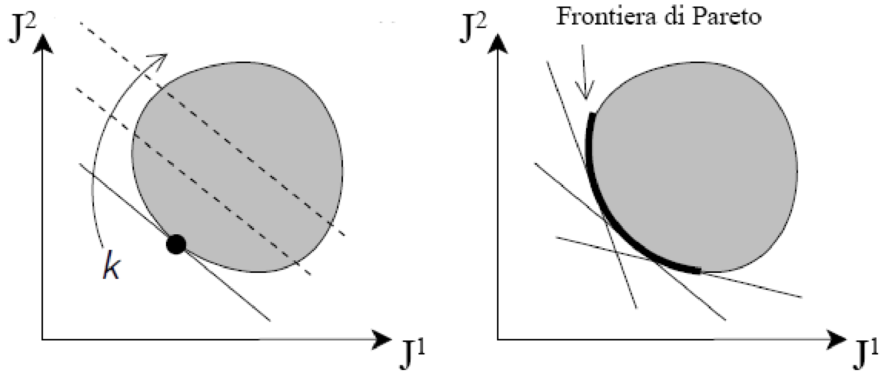


Figure 4.2: Solution of the Pareto frontier with weights method

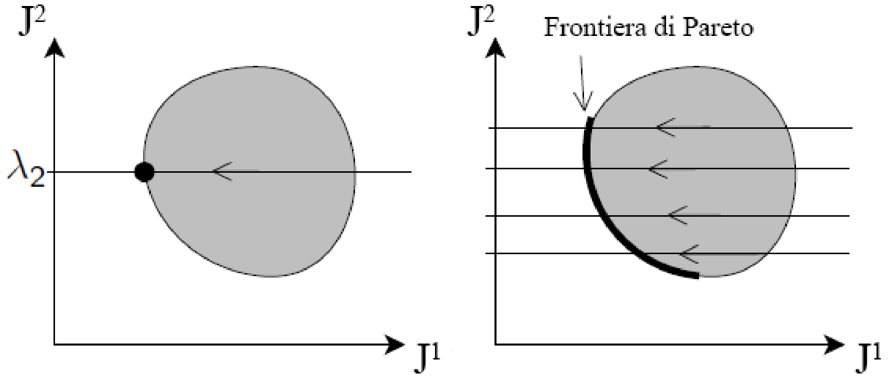


Figure 4.3: Soluzione frontiera di Pareto con metodo dei vincoli

The **constrains method** allows the creation of a scalar objective function from one of the components of the original objective function. The remaining $q-1$ components is transformed in constraints of the type $J^k \leqslant \lambda_k$.

$$J(u,\lambda) = J^r(u)$$

being:

$$J^i(u) \leqslant \lambda_i \qquad \text{con } i = 1,\dots,q \qquad i \neq r$$

Set the value of the coefficients λ_k , the parametric SO problem can be solved with standard optimization techniques to one goal. The result of optimization provides a Pareto-efficient solution of the original MO problem. Changing the value of the coefficients, it is possible to determine several efficient solutions as shown in Figure 4.3.

4.3 Deterministic programming

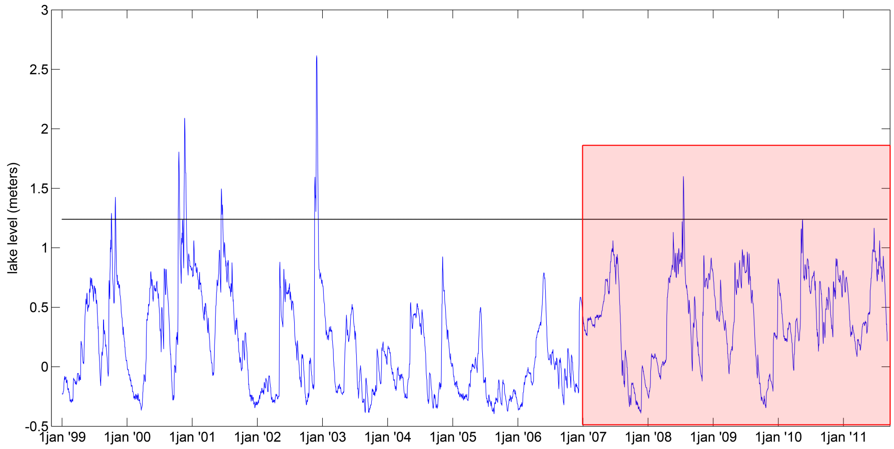
In order to define which parameters contribute to the definition of the controls of the lake, it will be used the deterministic programming to define the sequences of optimal controls.[3, 8] This algorithm takes as input the values of the inflows to the lake and the starting level of the lake itself at Malgrate hydrometer. Obviously this controls are not the historic ones but they are the best that could have been used. Using these controls as comparison value for the parameters, it can be define which ones contribute to a real improvement in performance. The series of optimal controls is not unique because they depend on the importance given to each of the objectives defined during the deterministic programming. So it is possible to generate a Pareto frontier, which is the set of best solutions in terms of Pareto efficiency. [24]

For the construction of the Pareto frontier it is preferred to follow the method of the weights. Taking care to choose the weights that would allow an optimal visualization of the curve, it is obtain the results shown in Table 4.1.

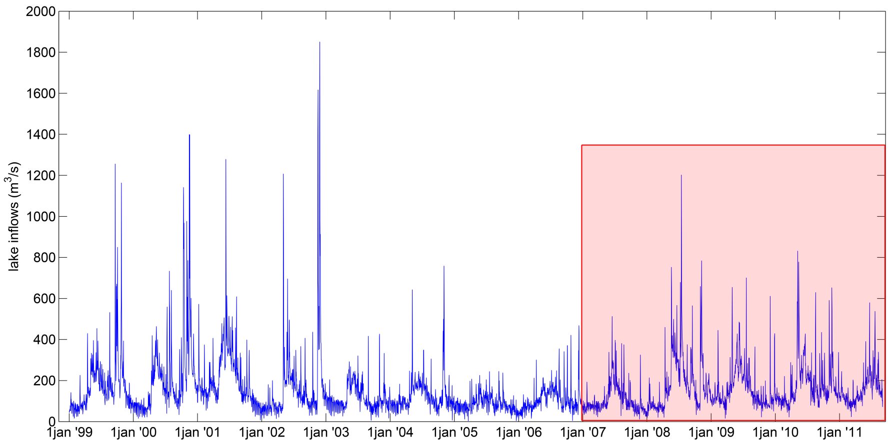
Flooding weight	Irrigation weight	Annual average of flooding days	Annual average of irrigation deficit (m^3/s)
0	1	122.00	221.22
1	0	1.75	502.14
$1-10^{-14}$	10^{-14}	1.75	408.31
0.000001	0.999999	28.75	221.22
0.9	0.1	6.00	221.17
0.5	0.5	8.75	221.15
0.999	0.001	1.75	224.15
0.975	0.025	4.50	221.21
$2*10^{-11}$	$1-2*10^{-11}$	36.25	221.22
$1-2.5*10^{-14}$	$2.5*10^{-14}$	1.75	312.44
$1-10^{-12}$	10^{-12}	1.75	235.62
$5*10^{-12}$	$1-5*10^{-12}$	56.75	221.22
10^{-14}	110^{-14}	84.25	221.22

Table 4.1: Pareto frontier weights with normal demand

Before continuing, it is necessary to anticipate that as a result of some comparisons made in later chapters, i.e. in Section 4.4.2 and in Section 4.4.3, and in relation to the results obtained in Figure 4.7, it was noted that the years under consideration were very few and didn't present any severe drought. In fact, available year are placed exactly in the middle of two highly drought periods, 2005-2007 and 2012, thus had an impact only in the first period of the first year taken into account. Looking at Figure 4.4a and Figure 4.4b, it can be noticed, infact, that the available data period, red marked, have no presence of



(a) historical lake levels



(b) historical lake inflows

Figure 4.4: Historical trends and considered period

any severe floods, as occurs in 2000 and 2002, or drought, as in 2003 and 2005.

Being this period not representative, and knowing that it is the lack of water to generate a strong conflict between the objectives analysed, it was decided to change some parameters in order to recreate this condition. In particular, the irrigation demand required by the farmers, has been increased by 20%.

In this way we tried to check the correctness of the method even in conditions worse than those available. By doing so, it is no longer possible to make a direct comparison with the existing control policies.

In Figure 4.5 are shown in green the points of the Pareto frontier in original condition, and in blue the points of the Pareto frontier with the increased irrigation demand.

As expected, increasing the irrigation demand increases the annual deficit irrigation and therefore, the frontier appears to be shifted toward higher values of this goal. At the same time, having a greater

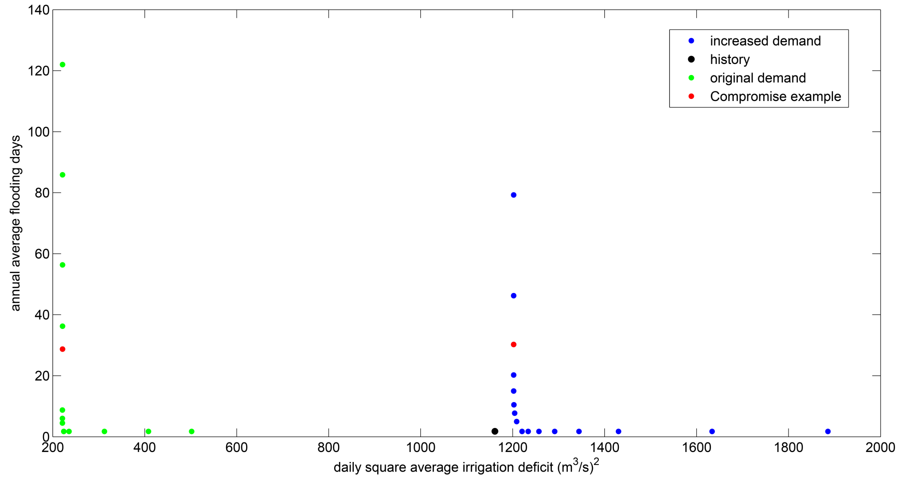


Figure 4.5: Pareto frontier, with and without increased demand, showing a possible compromise used as example in the following analysis

demand for water to be satisfied, the days of flooding, especially high ones, are reduced.

The black dot represents the current situation and can be compared only with the frontier with normal demand (green). It can be seen how the perfect knowledge of the inflows allows, for equal days of flooding, the possibility of a significantly lower irrigation deficit. If you wanted to go to a smaller deficit irrigation, it would be possible only raising the flooding day.

The two red dots correspond to the point of Pareto achieved by assigning weight as 0.000001 to the flooding and 0.999999 to the irrigation, which corresponds to a nearly extreme point of the frontier in favour of irrigation. These are the points that it was decided to use for further analysis.

4.3.1 *Results and comparisons*

The results deriving from the use of deterministic programming are the level of the lake and the excellent releases that could be achieved with the perfect knowledge of the inflows. Representing these two variables at the same time it is obtained the plot in Figure 4.6.

It can be immediately noticed the difference between the historical behaviour and the trend produced by the DP. The controller makes the decisions with a certain degree of safety and try not to get close to the limit of lake flooding, releasing greater amount of water than DP with the same level of the lake. The second thing that is noticed from this plot is the set of blue points with low release values and higher elevations of the lake. The algorithm, perfectly knowing the inflows, can afford to release less water with high levels of the lake knowing that the next few days will not reach flood level and therefore didn't risk overflows. This behaviour can improve the performance of irriga-

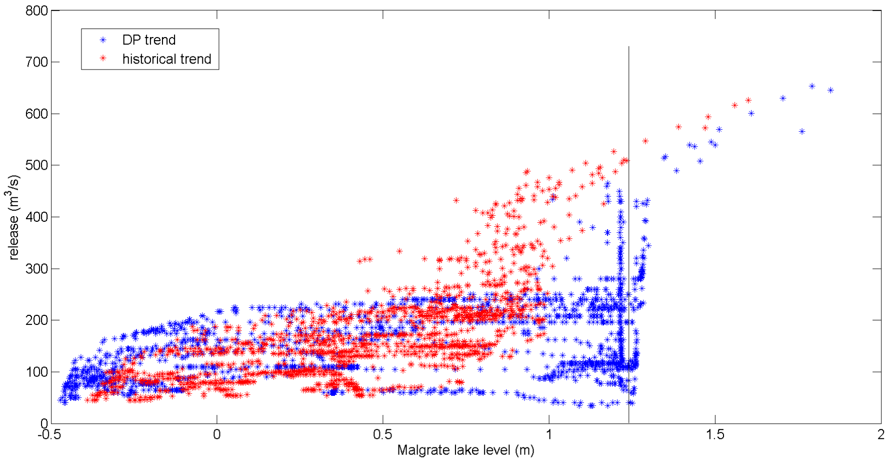


Figure 4.6: Releases trends depending on the level of the lake

tion. A final analysis concerns, instead, the high release values; once the lake is too much high, in both cases the controller decides to use maximum release in order to avoid damage.

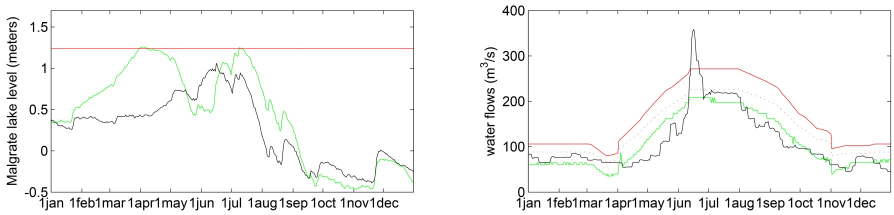
The blue values above the threshold of flooding should not surprising since, as was previously stated, it is considered a point in favour of irrigation and not of flooding. The values are still very close to the threshold but this value is the alarm threshold and not the flooding one. In fact the latter threshold is a few centimetres higher: 1.3 meters at the Malgrate hydrometer.

The Figure 4.7 show, for each year, the differences between the historical trend (shown in black) and the deterministic simulation (green lines) of the levels of the lake and comparisons between releases and irrigation demands. In particular, in the graphs on the left, the flooding of the lake is represented by a red line. The same line was used in the right graphs to represent the increased irrigation demand. The dotted line represents, instead, the original irrigation demand.

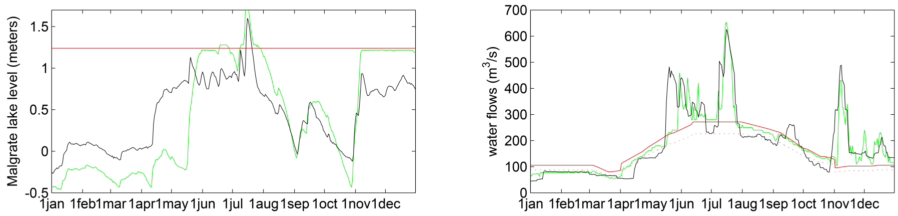
The basic results that emerge from this analysis is how deterministic programming is able, as already said, to keep the lake closer to the flooding threshold in order to allow a lower irrigation deficit. This can also be seen by comparing the releases with the demand. Today the manager of the lake uses a safety policy in favour of the flooding even when there would be no need. The controller releases from the lake more water than the one required fearing possible flood waves, while the releases trend of the DP, except when it coincide with a flood wave or when the lake is too full, follows better the course of irrigation demand.

Again, the fact that there are more days above the alarm threshold and that in 2008, during the only historic flooding, the DP has a worst behaviour, is dictated by the choice of the Pareto point.

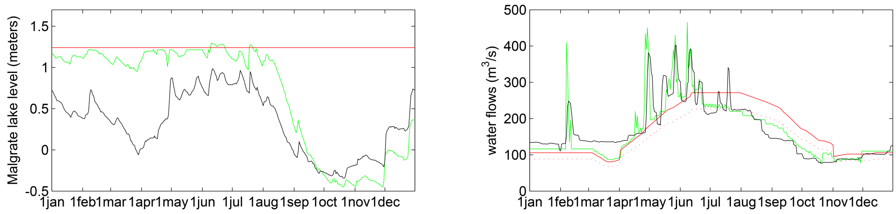
Other analyses using the opposite point, i.e. one in favour of flooding, have shown a marked improvement in performance as regards



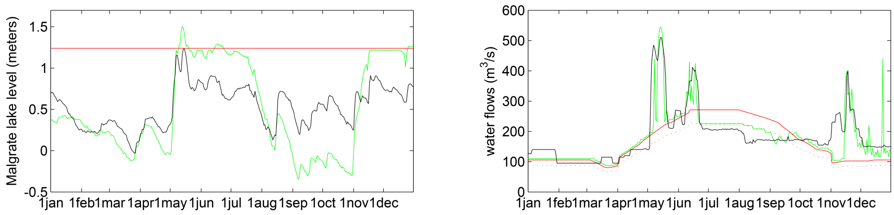
(a) comparison of 2007



(b) comparison of 2008



(c) comparison of 2009



(d) comparison of 2010

Figure 4.7: Comparison between DP results (both normal and increased demand) and historic trend

the days overflowed. In fact, the lake overflows only during the historical flood wave of 2008 with fewer days and with a lower highs of the lake.

4.4 VARIABLE SELECTION

There is available a large set of variables candidate to model the controls of lake Como identified by deterministic programming in Chapter 4.3. Therefore, arises the problem of identifying the subset of these variables that is able to provide the best performance.

4.4.1 *Input Variable Selection model*

A first version of the model consists of a simple hierarchization of inputs, where the candidate variables are ordered according to a statistical measure, the explained variance, that is able to tell how the variable taken into account explains the output data.

In theory, the first variable in this list should be the most significant in explaining the output. Actually, there may be redundant informations in the inputs. The contribution of each input with the same information is equally divided in the output explanation and, although very related with the exit, they wouldn't appear in the top positions of the ranking.

A better method is shown schematically in Figure 4.8 and it is called Iterative Input Selection (IIS) because it provides a iterative selection of inputs.

The first step consists, as in the previous model, in a hierarchization of the inputs according to their explained variance.

The first p variables are used as inputs for p Single Input, Single Output models (SISO), in order to rank the candidates on the variance. The best variable obtained from the comparison of the p models is added to the list of selected variables to explain the exit.

A multi-input single output model (MISO) is then used, adopting the variables chosen so far, to evaluate the performance and the output achieved.

The procedure is repeated using as new output the residues between the desired output and the output of the MISO model until the best candidate is not a variable already contained in the set of those chosen, or until the performance of the MISO model don't significantly improves or worsens.

At this point the best variables are those contained in the set chosen by the algorithm that provides an estimate of the output with performance equal to the final performance of the MISO algorithm (former to the one obtained for termination of the algorithm itself)(Figure 4.9).

4.4.1.1 *Models and evaluations contained in IIS model*

The evaluation of each model input is via *k-fold cross-validation*: the data set is divided into k subsets of equal size and filled randomly. The SISO model is run *k* times, each time using a different subset in

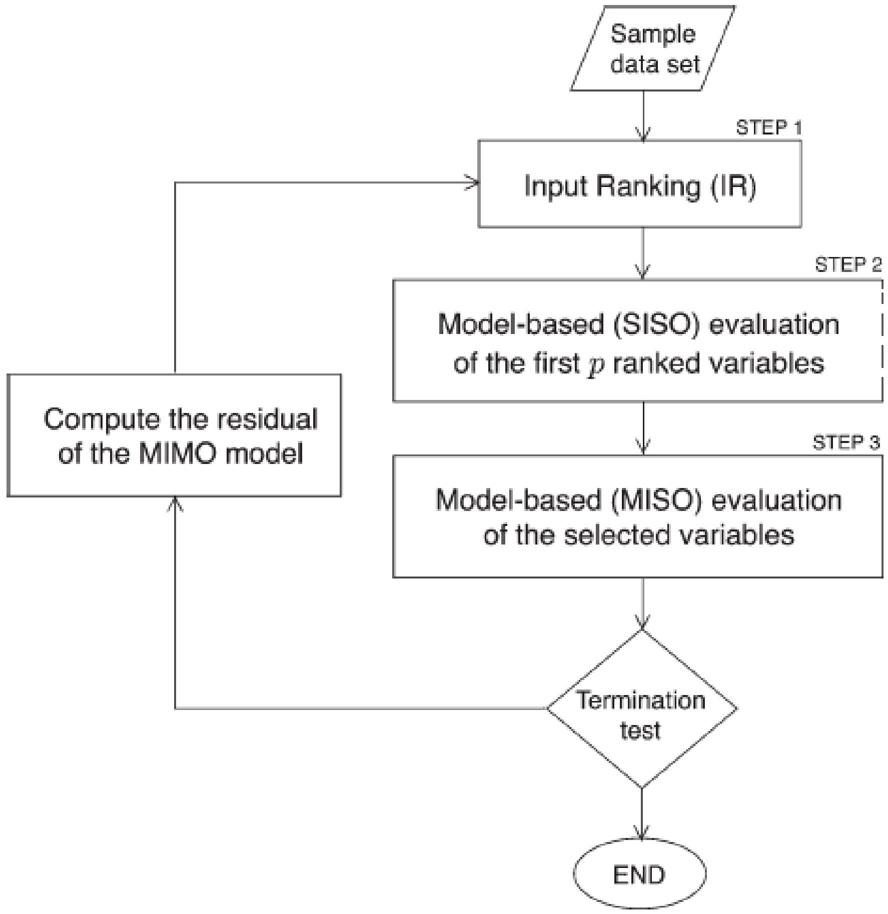


Figure 4.8: IVS Iterative algorithm scheme [14]

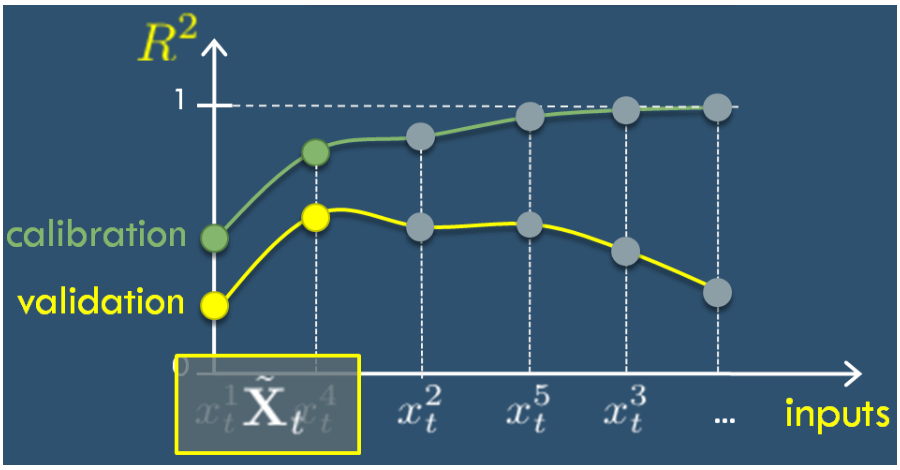


Figure 4.9: Trend of calibration, validation and variable selection with IIS method

validation, while the remaining *k-1* subsets are used for calibration. The performance of the model will then be the average of the performance of individual submodels so evaluated.

The IIS model was combined with an algorithm, the *Extremely Randomized Trees (Extra-Trees)*, based on tree models, that is able to automatically perform the ranking of the variables because its particular structure can be exploited to infer the relative importance of the input variables and to accordingly sort them.

The Extra-Tree, as we have said, is a non-parametric regression method based on tree models. All regressors are calculated using decision trees. These tree structures are composed of decision nodes, branches and leaves, to form a sequence of rules that lead to numerical values.

The tree starts with a first subdivision of the input into two subcategories, which form the first two branches, through a splitting criterion that will be used for the entire process. The subdivision process is then repeated for each branch until one arrives at a termination criterion, which can be the minimum number of elements within a leaf or the variation of the elements between a subdivision and the other. [7]

4.4.2 *IIS Results*

As mentioned in Section 4.3, there have been multiple investigations aimed to identifying the different behaviours in different situations.

4.4.2.1 *Complete period*

The Figure 4.10 shows which parameters are the best ones able to explain the performance of the controls in the worst condition, i.e. the one with the irrigation demand increased by 20%.

Analysing the results, it is clear that the best input is simply the temporal moment when the decision of release is made. In fact, this data explains more than 40% of the controls by itself. Moving forward, 75% can be reached taking into account the amount of "free" swe, i.e. the swe that is not intercepted by the mountain reservoirs, and up to more than 90% using the storage data referred to the hydroelectric lake in the basin of Adda.

The experiment was conducted 50 times with the same result for each of them, so we can say that we have obtained a strong result.

The policy of the lake is currently decided according to the day of the year and the level of Malgrate hydrometer. The lack of the level in the results raises some doubts. Therefore, the same experiment was conducted by removing the dates from the possible candidates to check if the signal brought by the days was repetitive compared

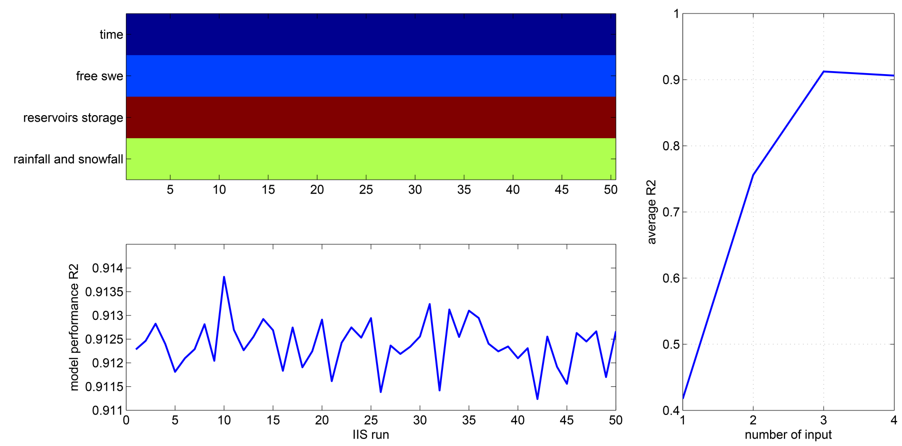


Figure 4.10: IIS result with increased demand

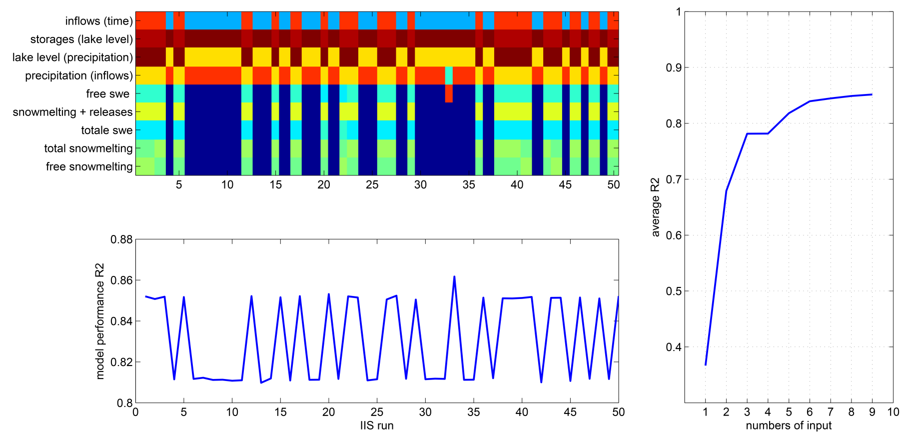


Figure 4.11: IIS results with original demand

to the lake level. In this experiment the level of the lake appeared, although not in the first but rather in the third position. Despite the loss of two positions the result suggests that the use of both of the data is redundant because the signal of one is contained in the signal of the other.

The second experiment was carried out with the same data and the same period, but using the original irrigation demand.

Looking at the Figure 4.11 it is noted that, during the various repetitions, the results were different.

It can be seen that the overall performance of the system is lowered from over 91% to a maximum of 86%. In addition, the algorithm, for almost half of the time, fails to go deep and reaches only 81%. This happens systematically when the mountain reservoirs are selected instead of precipitation, probably because of the activation of one of the termination conditions of the algorithm.

Despite this, the algorithm is uncertain only between two inputs and the results are readable anyway. It seems to be remarkable that in this case many variables related to the snow water equivalent appear

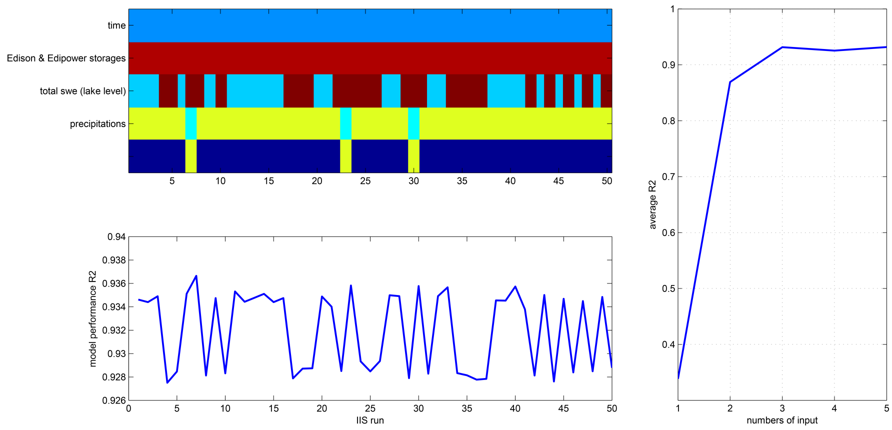


Figure 4.12: IIS results with separate mountain reservoirs

among the selected inputs, including the "free" swe, which brings a 5% improvement in performance.

In the Figure 4.12 were made some changes in the parameters given as input data in the IIS. Until now, it was used the mountain reservoirs as an aggregate variable for the sum of the single reservoirs. It was decided to divide these data, as was done in Section 3.5, according to the handler, because these reservoirs are placed at very different altitude, are subjected to different rules depending on the company that owns them, and especially they have completely different sizes.

This division was necessary because the a2a reservoirs, Cancano and San Giacomo, have a storage capacity equal to one third of all the hydroelectric reservoirs in the basin of Adda. Adding the Enel reservoirs, the storage easily exceeds half of the total. The division has provided that the reservoirs of a2a, as well as those of Enel, were considered independently, while those of Edison and Edipower are still considered as a single reservoir.

The result in the first position, the time of year, is not surprising because it is consistent with the results of the first analysis. The considerable fact is that the a2a or Enel reservoirs aren't in the second position, as might be expected, but those of Edison and Edipower are.

One possible explanation is that these reservoirs are smaller and placed at a lower level than the other reservoirs and thus, failing to provide large quantities of water or snowmelt, they have a similar patterns as those of Lake Como.

In this experiment we also find, as result, the level of the lake, but it is in competition with total swe. Swe proves to be the winner because the total system performance are lower when the level of the lake is selected.

As a conclusion of these analysis we can say that the results deriving from increased demand are more solid and provide a better fitting

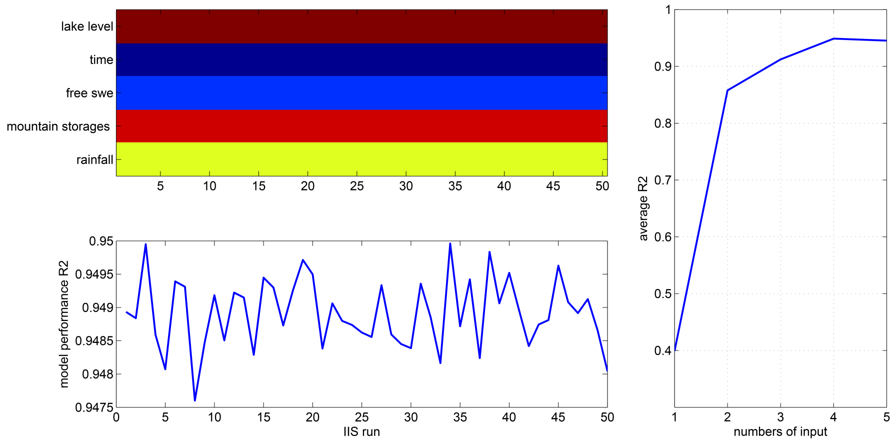


Figure 4.13: IIS results in the period between April and October

of the DP controls. Even better are the results of the experiment with divided reservoirs. In all experiments the time is in first position, partially coherent with the actual policy. The snow information and the storages are the second and the third variable considered important.

4.4.2.2 *Focus on the irrigation period*

Remembering the short length and the unrepresentative situation of the time series, other analysis have been made, taking into account only the sub-period running between April and October, which is the irrigation period.

Using this period, the increase irrigation demand and the divided reservoirs, there has been a deterioration in performance below the 90%, which would indicate that is preferable to use the entire available period for better management of the lake, instead of focusing on the period with major problems or with major interest.

A second note must regards the selected variables. The algorithm prefers to use the level of the lake in place of the period of the year. The other variables are the, same except for the addition to the selected ones of the a2a reservoirs and the total swe.

The next pair of analysis was carried out using in both cases the sub-period from April to October.

The Figure 4.13 shows the results of the first analysis, carried out with the increased demand, in which we can see that the statement made earlier, about the possibility of using the level of the lake instead of the date, is false. In this case, in fact, both the data are required and they can explain the 85% of controls carried out on the lake.

Reminding the goal of this study, it remains satisfied in finding the "free" swe in third place, which helps to increase performance by about 7%.

This particular case, among all the analyses carried out, owns the best performance, slightly higher than the the separated mountain reservoirs case.

For the second analysis, the sub-period has been maintained, and the original irrigation demand was used in place of the increased demand by 20%.

The results obtained are in line with the other results obtained so far: there is a general system performance loss, the level of the lake is no longer between the important variable, the variable concerning the free swe lifted in second position.

4.4.3 *Regression*

The IIS algorithm provides only the list of the variables more related to optimal control and their degree of correlation, but does not provide the control achieved by the use of those variables. To achieve this goal, it is carried out a regression through Extra-Trees, starting from a single input variable and then adding one at a time. This way the value of the different controls can be calculated if a certain number of variables were used as input.

The best way to compare the controls obtained through deterministic programming and those derived from regression, is through the scatter-plot. As a further analysis of correctness certain significant periods are placed in relation, in particular, a period that coincides with a flood and a period coinciding with low water. The result of this analysis is purely graphic and provides the degree of adaptation of the regressors to the controls deriving from the DP.

The tests carried out are exactly the same as the tests carried out using the IIS algorithm, but are graphically shown only those results considered significant.

In the Figure 4.14 the trends of the regressors are shown compared with the controls of the DP for increasing number of inputs. The best result would be the one with all points in line on the bisector of the quadrant. There is a significant improvement increasing the number of inputs used, except in the last case that, as also seen in the results of the IIS, provides no significant improvement.

The fit degree is comparable with previous results. Graphically, there is a differences in data only for high values of control, where the deterministic admits higher values compared to the ones derived from regression.

The performance of low water, shown in Figure 4.15, is followed regularly until you don't consider the trend arising from using only one input; this also happens to the floods, even if the peak value is not reached, and the two floods appear to be mediated along the period between them. This fact, however, is consistent with the images of

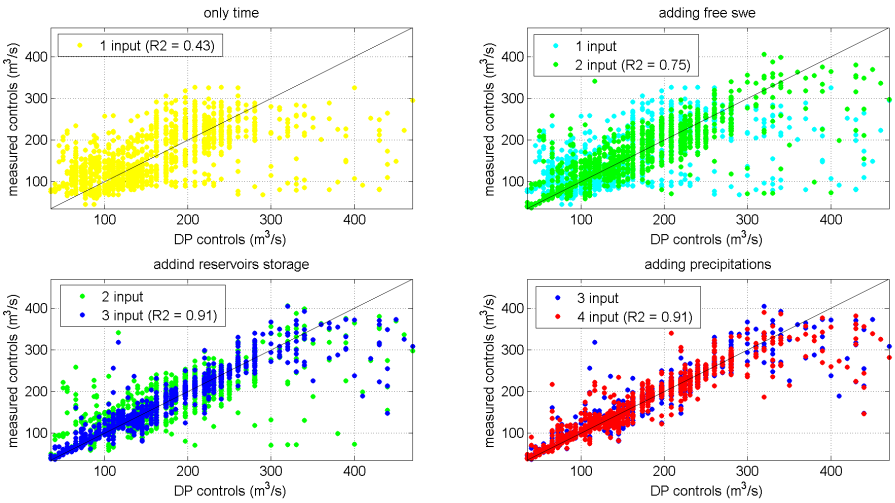


Figure 4.14: Regression with increased demand

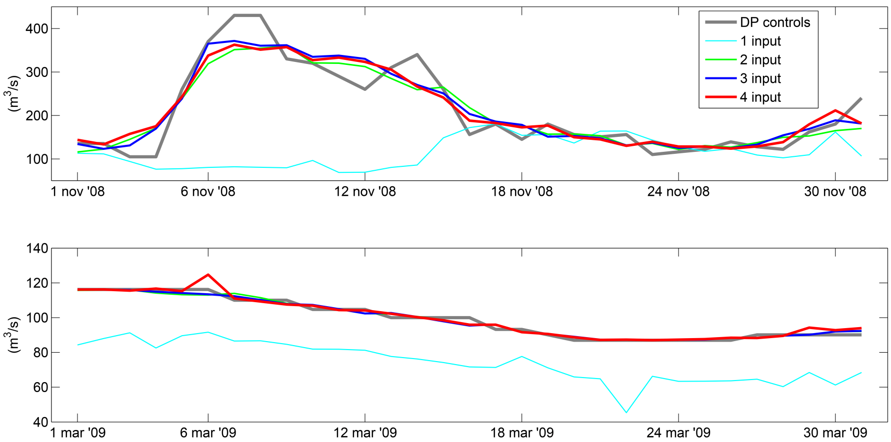


Figure 4.15: Comparison between floods and low water periods with increased demand

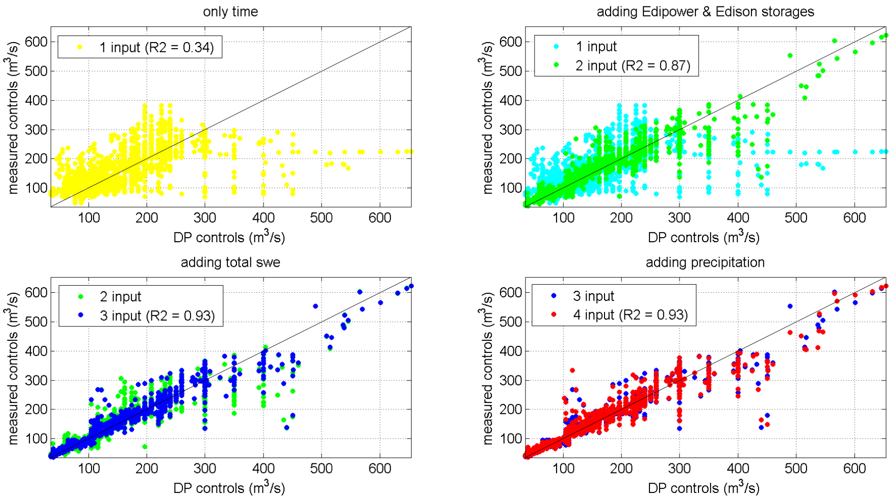


Figure 4.16: Regression with divided reservoir

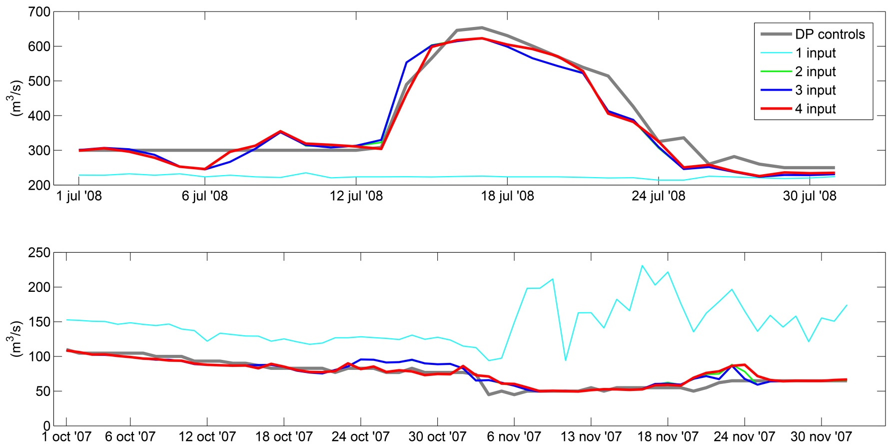


Figure 4.17: Development of floods and low water with divided reservoirs

the scatter-plot that shows the maximum values of the controls lower than those in DP.

The Figure 4.16 shows the results of the regression after the division of the reservoirs according to their owners. Through the only day of the year, it's not possible to obtain controls that exceed $400m^3/s$ while the deterministic owns values that exceed $600m^3/s$. This is also visible in the Figure 4.17 in the plot of the flood, where the line corresponding to a single input does not see the rise of the curve.

With more input, instead, high values manage to be intercepted, in fact the curve of the flood results to be followed quite well. In this experiment, the values ranging between 300 mc/s and 500 mc/s are a bit lower than they should be.

The plot of low water turns out to be completely busted if the trend of a single input was looked, while there was significantly improvement using at least two inputs.

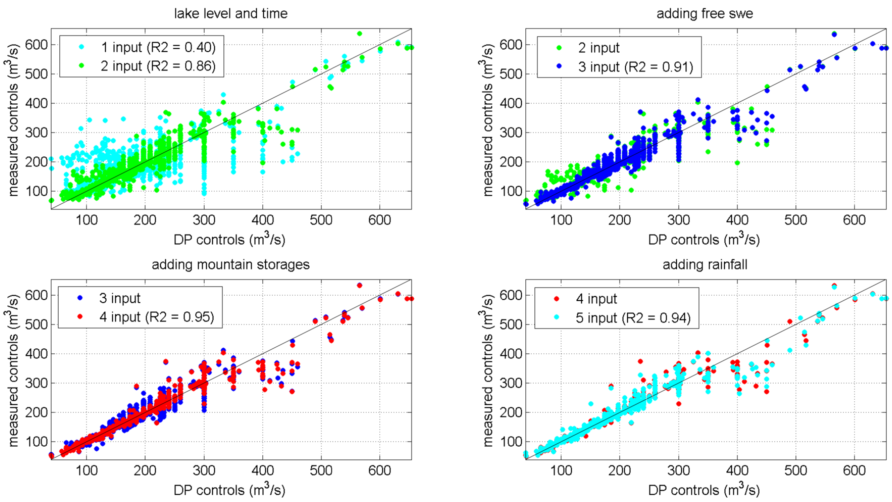


Figure 4.18: Regression with divided reservoirs and April-October sub-period

Even in this case the fourth input is significantly influential and performance results are compatible with the results of IIS.

Simultaneously with this experiment, the experiment with the separated reservoirs and the reference period shortened to the months between April and October was carried out.

The results are very consistent with the IIS and also with the regression just made. The worst data are, in fact, located between 450m³ and 500m³. The range is then improved, but the values are much lower.

The performance modelled the trend of the variables selection and, even in this case, the last input is not significant.

Remarkable differences are found in the progress of low water, where you need the third input to see the improvements. The progress, however, are not at the level of the experiments carried out so far. The trend of the floods are better.

The last documented experiment is related to the increased demand by 20% and limited to the period between April and October and shown in Figure 4.18 and Figure 4.19.

As mentioned in the previous paragraph, this is the case that produces the best output. The regression, in fact, reaches a degree of adaptation equal to 95 % even if the last input produces a decrease in performance.

The adaptation to the flood turns out to be one of the best (considering the fourth input and not the fifth) and it is able also to obtain the peak value of the flood, although slightly in advance respect to the real one.

For completeness, we calculated the regression even in case of the original irrigation demand and considering the period between April and October. The performance, as expected, decreases, while it is

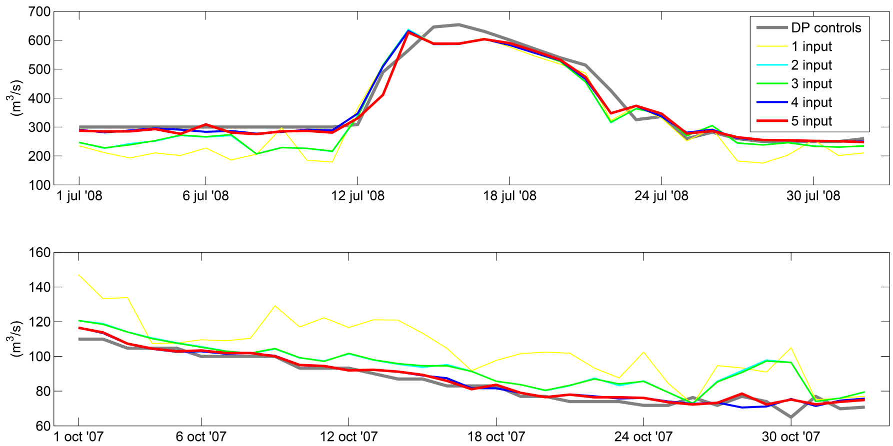


Figure 4.19: Comparison between floods and low water periods with divided reservoirs and April-October sub-period

noted that the fourth input carries a net loss of performance. In this case high values of control can not be found by regression, and it leads to a flood curve lower than that obtainable by deterministic programming. Even the dry period fails to be adapted properly because, with any input, the values remain above the optimal curve.

4.4.4 *Conclusions*

At this point it may be useful to remember the purpose of the research, which is to determine whether there are variables that can improve the management of Lake Como to a Pareto efficient value and, in particular, if one of these parameters derives from the knowledge of the amount of equivalent water stored in the form of snow in the Alps.

The results obtained through the iterative input selection suggest that there are at least two candidate variables to answer these questions, in particular the alpine reservoir and snow water equivalent.

Depending on the experiments, these data can be decomposed into some of their derivatives because the swe appears in both the total component and in the "free" component, i.e. the one that is not captured during its melting; mountain reservoirs, instead, always fall between the candidate variables, and in particular a subgroup, i.e. the sum of the reservoirs managed by Edison and Edipower.

To confirm the results obtained so far, the next chapter will be devoted to optimize the management of Lake Como, having in input, as well as the time, one or both of the considered inputs. Moreover, given the lack of robustness of the results with the original irrigation demand, the experiments will be carried out only with the irrigation demand increased by 20%.

4.5 CONTROL POLICY OPTIMIZATION

The operation problem of water management could be solved via Stochastic Dynamic Programming. But there are a few problems using this method: the growth of the computational cost of SDP with state and decision, and the single-objective method for the resolution of the problem.

So it is decided to use a Direct Policy Search combined with multi-objective evolutionary algorithms (MOEA), in order to solve high-dimension state and control space problems and find an approximation of the entire Pareto front, and the associated control policies, in a single optimization run. [5, 19]

DPS is a simulation-based approach where the control policy is first parametrized within a given family of functions and then the parameters optimized with respect to the objectives of the control problem. The selection of a suitable class of functions, which the control policy belong to, is a fundamental operation, as it might restrict the search for the optimal policy to a subspace of the decision space that does not include the optimal solution.

It is decided to use universal approximators because they should be capable of accurately estimating any unknown continuous function under very mild assumptions.[22] In this particular case the Radial Basis Function was used instead of the Artificial Neural Network because as said in [15] the RBF provides better results.

The multi-objective optimization of the policy parameters is performed using the self-adaptive Borg MOEA, which has been shown to be highly robust across a different suite of challenging multi-objective problems. This algorithm combines adaptive operator selection with ϵ-dominance, adaptive population sizing and time continuation. The resulting algorithm is designed for handling many-objective, multi-modal problems from a wide assortment of problem domains.[22]

4.5.1 *Experiment setting*

The operating policy has been calculated several times, each time increasing the number or the input variable. By changing the number of input it was necessary to vary the number of radial basis and consequently the number of the parametrizations.

Depending on the considered experiment, it was used one of the following parametrizations:

- 2 inputs, $\sin(2\pi t/365)$ and $\cos(2\pi t/365)$, with 3 RBF and 15 parameters;
- 3 inputs, $\sin(2\pi t/365)$, $\cos(2\pi t/365)$ and lake level, with 4 RBF and 28 parameters;

- 3 inputs, $\sin(2\pi t/365)$, $\cos(2\pi t/365)$ and free swe, with 4 RBF and 28 parameters;
- 4 inputs, $\sin(2\pi t/365)$, $\cos(2\pi t/365)$, free swe and reservoirs storage, with 4 RBF and 45 parameters;
- 3 inputs, $\sin(2\pi t/365)$, $\cos(2\pi t/365)$ and Edison & Edipower reservoirs storage, with 4 RBF and 28 parameters;
- 4 inputs, $\sin(2\pi t/365)$, $\cos(2\pi t/365)$, Edison & Edipower reservoirs storage and total swe, with 4 RBF and 45 parameters;
- 4 inputs, lake level, $\sin(2\pi t/365)$, $\cos(2\pi t/365)$ and free swe, with 4 RBF and 45 parameters;
- 5 inputs, $\sin(2\pi t/365)$, $\cos(2\pi t/365)$, free swe and reservoirs storage, with 4 RBF and 66 parameters;

We include time t among the policy inputs by means of the terms $\sin(2\pi t/365)$ and $\cos(2\pi t/365)$, to take into account the time-dependency and cyclostationarity of the system and, consequently, of the control policy. Since the Borg MOEA has been demonstrated to be relatively insensitive to the choice of parameters, we use the formula:

$$num\theta = NN(2MM + K)$$

where θ is the number of parametrizations, NN the numbers of the basis, MM the numbers of the input and K the number of decisions that in the study case is equal to 1.

Each optimization was run for 250000 function evaluations. To improve solution diversity and avoid dependence on randomness, the solution set from each formulation is the result of 10 random optimization trials.

4.5.2 *Application results*

It must to be made a clarification. The settings proposed in the previous paragraph are correct up to the inclusion of the third input. With the addition of the fourth input (or the fifth), the policy we are looking for becomes too complex and therefore the algorithm does not reach convergence. The change of the settings covered the number of evaluating function, which changes from 250000 to 300000, and the increase of the randomized starting points. Doing so, we will try to start the algorithm at different points that could generate better policies; the same policies are then evaluated a greater number of times.

As a first comparison, in Figure 4.20, are shown the optimal Pareto frontier (black dots), deriving from Deterministic Programming, and the Pareto frontier deriving from the application of this method with time and lake levels as inputs (blue dots). The space between the two

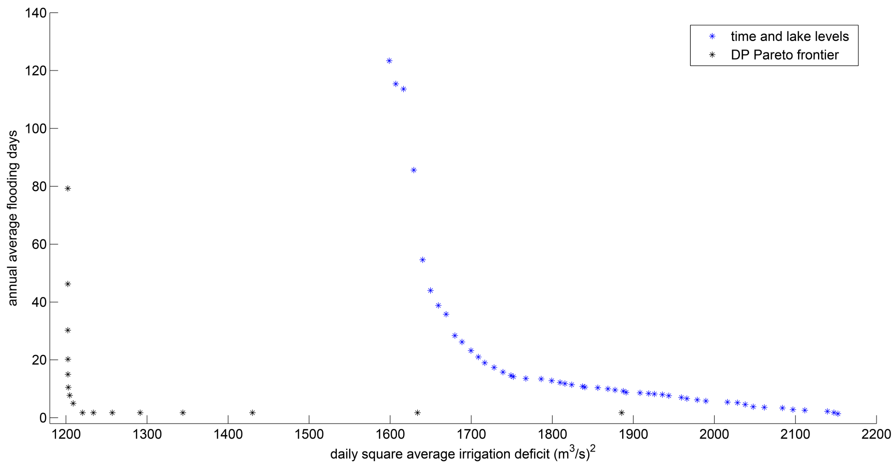


Figure 4.20: Comparison between Pareto frontiers deriving from DP and from use of usual inputs

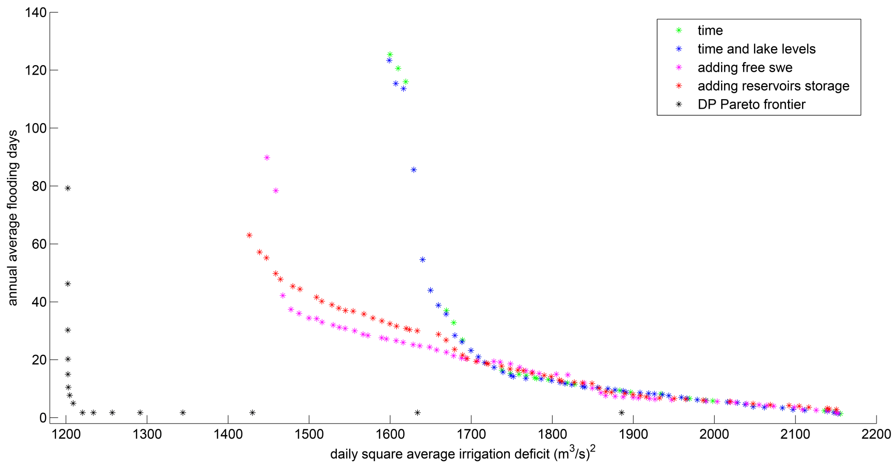


Figure 4.21: Comparison between Pareto frontiers with increased demand

frontiers is the improvement zone that can be reached using the hydroclimating information. The ideal solution is located in the bottom-left corner.

The first analysis was carried out with the results of the IIS algorithm performed with the increased irrigation demand. The results are shown in Figure 4.21. The green frontier was the one obtained using only the two time series ($\sin(2\pi t/365)$ and $\cos(2\pi t/365)$). As imagined in the previous chapter, the addition of the lake level in the optimization policy does not improve the management of the lake. It can be seen this by comparing the green and the blue Pareto frontier. The difference is minimal.

The magenta and red frontiers represent the adding of the free swe information and the reservoirs storage, respectively. It can be noticed that these two frontiers are closer to the one obtained via DP, at least from the value of irrigation deficit equal to $1700(m^3/s)^2$. In

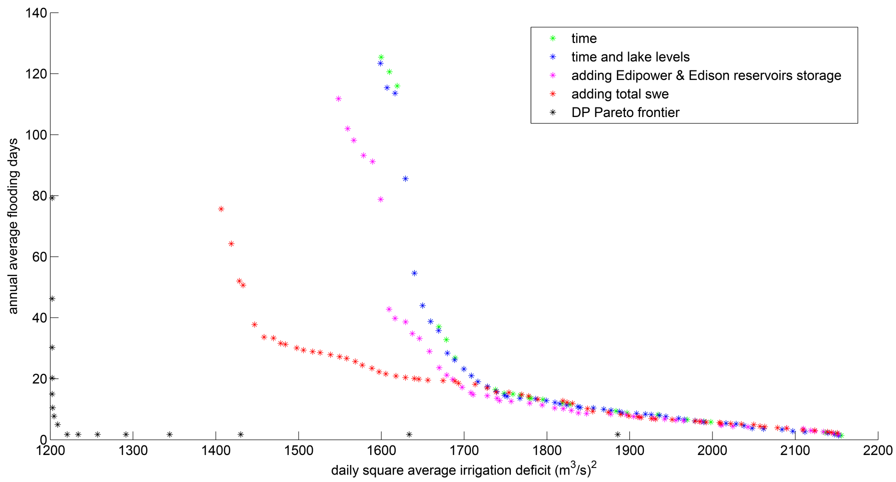


Figure 4.22: Comparison between Pareto frontiers with divided reservoirs

particular, there is the best improvement along the irrigation deficit objective because a small variation in the flood days produce a great improvement in the irrigation deficit.

The red dots should have been closer to the Pareto frontier of the DP than the magenta points, or at least superimposed to the magenta points. This does not happen because, as mentioned earlier, even by altering the parameters, the algorithm fails to reach convergence or the starting points are not too representative. Only points with most days of flooding manage to have the irrigation deficit better than the one obtained with the free swe.

It is needed to remember that there are few floods during the considered horizon and that would be needed forecast data forward in time to decrease the objective of flooding days. Infact, the only improvement of this objective indirectly derives from the decreasing of the conflict.

The second analysis was performed always using the increased irrigation demand, but with the divided reservoirs storage. The results are shown in Figure 4.22 and even in this case the green frontier represent the use of the time alone. The magenta and red frontiers are achieved by adding Edison and Edipower reservoirs storage and the total swe, respectively.

In this case the addition of the total swe involves the closest Pareto frontier to the utopia point. The utopia point, as we said in Section 4.1, is the point that is obtained by minimization of one objective at a time. So this is the best solution but it can't be achieved if the objectives are conflicting.

This case was correctly because the Pareto frontiers are getting closer and closer to the border of the DP with the growth of the inputs used.

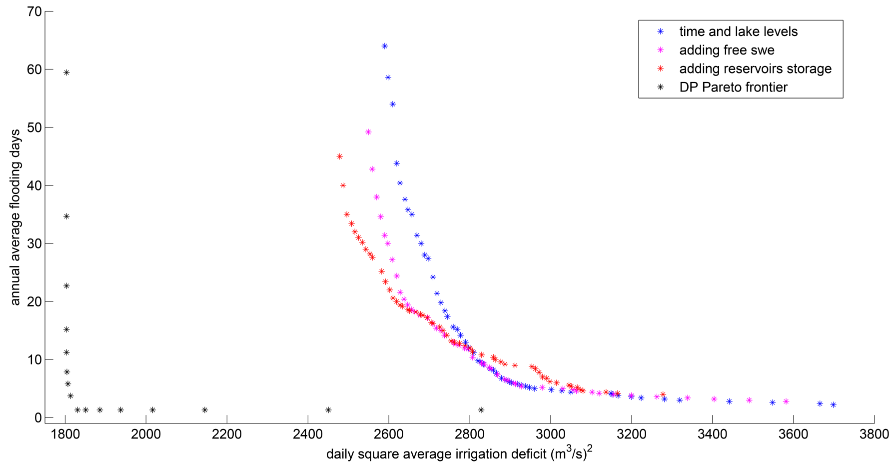


Figure 4.23: Comparison between Pareto frontiers with the use of sub-period April-October

The tails of all frontiers are practically superimposed. This means that for those objectives values, knowledge of hydroclimatic parameters needs only to improve the irrigation deficit.

The last analysis was performed using the increased demand but only with the sub-period between April and October. The results are shown in Figure 4.23. The presence of higher values of irrigation deficit target is one of the first things that should be noted. This happens because it is taken into consideration only the summer period, which is the one with the greater water demand for irrigation. So the deficit irrigation is not mediated with the rest of the year during which it should be absent.

The green frontier is no longer present because, as found in Chapter 4.4.2, the results of the algorithm input selection suggest as first variables both the level of the lake and the date. These two variable are already contained in the blue frontiers.

The order of the input corresponds to the degree of improvement of the frontiers. Also in this case it is noted that for high values of irrigation deficit and low values of flooding days, the addition of information to the current policy provides benefits only at irrigation deficit. Benefits which are instead present in the area closest to the DP frontier.

In conclusion, we can say that these experiments have confirmed the results obtained via Input Variable Selection. So it can be said that the knowledge of hydroclimatic information can bring benefits in the management of regulated lakes.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

This research was aimed to check whether there were other variables, in addition to those already used by the regulator (i.e. inflows and the storage of the lake), which can improve the management of Lake Como. The knowledge of swe, in addition to time, is fundamental to the study because it was thought that the best possible variables were those deriving from this type of data.

From the study of the methodologies for the snow data acquisition and consequent analysis carried out in this research, it is clear that, despite continuous improvements in technologies, the estimation of the snow water equivalent is still an estimate and not a precise data. Further analyses, such as those proposed here, should be made after an improvement in the nivo-meteorological network present in the territory, including an increase of measuring stations, and developing more accurate methods for the evaluation of the snowpack. Also the time series of these data should be extended because until now the snow data are available only for the period 2007-20012 that allows only the use of the calibration at the expense of validation.

As an element of comparison, for determining the performance of the other variables, we used the sequence of excellent controls obtained by the Deterministic Programming. The Pareto frontier that derives from it, is the result of the optimization of two objectives, the daily average of irrigation deficit and the flood days. However, it should be remembered that, to get a more accurate results, should be considered all the others objectives, such as the income of the hydroelectric power plant located further downstream or the environmental objective.

The results obtained from the Iterative Input Selection algorithm put in the first place the day of the year or the lake level, while in second and third position, depending on the experiments performed, the storage of mountain reservoirs, the free snow water equivalent or the total swe. The top positions are coherent with the current policy, which uses both the day of the year and the storages for the management of the lake. The other results answer the question that we have placed: the information coming from the knowledge of the mountain snow water equivalent can bring improvements to the management of the lake.

To evaluate the degree of improvement with the use of this information, it is performed a Direct Policy Search with a Multi-Objective Evolutionary Algorithm for the creation of the Pareto frontiers, that would reflect the optimization of the policy according to the inputs used.

It is to remember that the snow data are available only in a short period of time. Therefore it was not possible to use some data for the validation. The results that were obtained are those derived from the calibration.

Results show that the only use of the time is not sufficient to improve the objectives. It is needed the addition of at least one hydroclimatic information to improve the irrigation deficit and indirectly, the flooding days. The best variables have proven to be the free and the total snow water equivalent, as well as the sum of the Alpine reservoirs storage. The more inputs are used, in agreement with the IIS results, the more the Pareto frontiers improve and hence the management of the lake is improved. Despite this, it remains far from optimal policy and then you can think that there are still other information that could lead to further improvement.

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