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MASTER THESIS

**A Comprehensive Analysis of the climate
change and structural Uncertainty on a Complex
Water Supply System**

Case study in Como-Muzza, Lake-Agricultural District

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for the degree of Master Thesis*

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Declaration of Authorship

I, Slaven Conevski , declare that this thesis titled, C and the work presented in it are my own. I confirm that:

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Date:

‘The history of mankind can be written in terms of human interactions and interrelations with water. ’

Biswas, 1970.

Abstract

Master of Science

**A Comprehensive Analysis of the climate change and structural
Uncertainty on a Complex Water Supply System**
Case study in Muzza Agricultural District and Como Lake

by SlavenCONEVSKI

Climate change models uncertainty analysis are quite addressed in the literature, especially after each IPCC report. In fact they offer comprehensive statistical information about the uncertainty of each GCM or RCM. In addition, the CC impact on the water resources is also well elaborated by numerous of studies and even governmental reports that offer guidelines for CC mitigation and adaptation. Anyway, after the AR5 was published, introducing the new concentration pathways and the new regional down-scaling framework EUROCORDEX, there are still no strong assessments and case studies that will assess the new approach and the uncertainty that follows.

Over the decades, using Global Circulation Models to simulate future climate scenarios have been proved applicable and useful for depicting plausible future conditions and for climate change impact studies. However, given multiple GCMs simulations that are tuned to run under different assumptions (or initial conditions), a comprehensive uncertainty analysis is necessary in order to better understand those projected future conditions and its implications, as was done by IPCC in its Assessment Report. On the other hand, many studies on the climate change impact tend to use only a few projections within the impact assessment model, without justifying their choice of the scenarios. Moreover, small number of projections may also overlook the consequence due to the uncertainty in the GCM outputs. In this study we offer a broad vision by investigating many up-to-date GCMs outputs available from latest IPCC project, and evaluate their impact on a complex water system within a decision-analytic modeling framework.

The studies starts with a detailed statistical analysis of the projected temperature and precipitation. Followed by assessment of their impact on the water related activities in Lake Como basin as well as the downstream irrigation districts represented by Muzza. The specific features of our approach, applied through complicated multiple model simulations are: i.) Inflow generation, ii.) impact quantification based on a set of performance indicators, considering both upstream and downstream stakeholders; ii.) designing management policies, by meanings of optimal control techniques; iii.) preserving the multi-objective nature by Pareto Frontiers generation, evaluating the indicators and the

uncertainty produced by different GCM/RCM combinations. After the application of suggested framework, the three conflicting objectives are discussed under baseline, CC and co adaptive simulation. The water deficit and the farmers profit are more likely to be highly impacted of the CC, while the flooding stands more inert for some projected results. While the analysis run, we discuss the "inner" uncertainty of the CC scenarios, and prove that is rather significant. However the structural, modeling uncertainty is the most significant, despite the natural variability contribution is important and over cross with other sources of uncertainty. Notwithstanding the robustness of this analysis we offer a simple planning measure for successful mitigation and adaptation strategies facing the CC impacts.

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This is hilarious, but it is a template...and it is true. :D

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Abbreviations

IWRM	I ntegrated W ater R ecourses M anagement
WFD	W ater F rame D irective
PIP	P articipatory and I ntegrated P lanning
CORDEX	C oordinated R egional C limate D ownscaling E xperiment)
RCP	R epresentative C oncentration P athways
HBV	H ydrologiska B yrans V attenbalansavdelning- rainfall-runoff model
CC	C limate C hange
GCM	G lobal C irculation M odels
RCM	R egional C limate M odel
QQ	Q uantile probability plot
SDP	S tochastic D ynamic P rogramming
CDF	C umulative D istribution F unction
STD	S Tandard D eviation
MASH	M oving A verage S hifting H orizon
MAS or MABS	M ulti A gent based S ystem
DCOP	D istributed C onstraint based O ptimization P roblems
AI	A rtificial I ntelligence
DM	D ecision M aker
CAP	C ommon A griculture P olicy
BMP	B est M anagement P actices
EEA	E nvironmental E uropean A gency
IPCC	I ntergovernmental; P anel on A gency C limate C hange
AR5	A ssessment R eport 5 fifth
FAO	F ood and A griculture O rganization

Symbols

H	Horizon (years)
s_t	storage (m^3)
n_t	inflow (m^3/s)
x_t	state variable (/)
r_t	lake release (m^3/s)
q_t	river flow (m^3/s)
ε	disturbance (/)
h_t	water level (m)
ϕ	probability distribution of a variable (/)
u_p	planing action (/)
u_t	management control (/)
p	set of controls, policy
$m_t(\cdot)$	control law, controls
J	objective function (/)
J^{flood}	flooding obj function (m^2)
J^{irr}	water deficit obj function ($(\text{m}^3/\text{s})^2$)
w^{flood}	weight associated with the flooding (/)
w^{irr}	weight associated with the water deficit (/)
$W(w_t)$	water demand (m^3/s)
$T(ts)$	surface temperature ($^{\circ}\text{C}$)
$P(pr)$	precipitation (mm/day)

Chapter 1

INTRODUCTION

1.1 Context and Motivation

Scientific evidence of climate change is univocal (IPCC, 2007). As climate change warms the atmosphere and alters the hydrological cycle, we will continue to witness changes to the amount, timing, form, and intensity of precipitation and the flow of water in watersheds, as well as environmental quality. The relationship between the natural and the anthropic system is a significant one. More and more, that relationship is falling out of balance jeopardizing food, water and energy security. Climate change is a phenomenon we can no longer deny as its effects have become increasingly evident worldwide. On the list of warmest years on record, almost every year since 1992 is included and, according to NASA and NOAA data, 2012 was the hottest. Unexpected extreme events and storms lead the planet towards high natural uncertainty. This is consequently followed by various hazards, like droughts, floods, hurricanes etc.

The climate change does not introduces changes only in the atmosphere but also in the human behavior and habits, the nature, the society, the economy. Here arises the light motive of this study.

Water is the primary medium through which climate change influences Earth's ecosystem and thus the livelihood and well-being of societies. Higher temperatures and changes in extreme weather conditions are projected to affect availability and distribution of rainfall, snowmelt, river flows and groundwater, and further deteriorate water quality. The poor, who are the most vulnerable, are likely to be adversely affected. As a result of growing populations, rapid and extensive industrialization, and over-allocation and

mismanagement of freshwater resources, a looming global water crisis that is said to be "unprecedented in human history" has been predicted.

Water resources and how they are managed impact almost all aspects of society and the economy, in particular health, food production and security, domestic water supply and sanitation, energy, industry, and the functioning of ecosystems. Under present climate variability, water stress is already high, particularly in many developing countries, and climate change adds even more urgency for action. Without improved water resources management, the progress towards poverty reduction targets, the Millennium Development Goals, and sustainable development in all its economic, social and environmental dimensions, will be jeopardized.

In this part it should be highlighted that as the water resources are facing uneven, limited distribution, the hydro-power, irrigation and the drinking water supply would be the main conflicting point in the water resources allocation.

Still, the management of the water resources is not naive. On one hand there are many stakeholders involved with different objectives, and on the other we have the dynamical evolution of the climate change boundary.

Glacier melting, increased evaporation rates, a higher proportion of precipitation received as rain, rather than snow, earlier and shorter runoff seasons, increased water temperatures, and decreased water quality are the main implications of the CC for water resources. This implies that we must start to increase our awareness and rationally manage water resources. In fact climate change reveals uneven distribution of the water resources. However, water systems have different purposes. It might include irrigation, water supply, tourism, navigating, etc. Agriculture is by far the largest water user in the World and in Italy: it can be estimated that nearly 2/3 of available water resources are used for irrigation. On the other side we have the regulated lakes, which water regulation policy is confronted among many conflicted stakeholders. Also far more relevant is the impact that irrigation has on river outflow patterns and management of lakes and reservoirs if the issue of "minimum environmental or natural flow", linked to environmental, recreational and landscape water uses, has gained attention and importance; if the traditional meaning of "reclamation" is now perceived as environmental un-friendly (e.g. for the sake of wetlands conservation), it must be stressed however that irrigated farmland and artificial drainage are activities lasting for many centuries, particularly in Northern Italy, and contributed strongly to the creation of the rural landscape. For the Como lake catchment feed from the alpine streams, we might say that this region

is quite abundant considering the world average. Having the uneven distribution and faster snow melting, or shifting inflow/outflow peaking might be easily managed if we do not have the problem of flooding the shore towns, and the damage caused, not just financial but also the historical and touristic reputation.

Thus, one can bare in mind that we can not only focus on water resources if we want preserve the water system. We need integrated participatory water resources management (IPWRM).

1.2 Thesis Goal and State of Art

The significant influence of the Climate Change on the water resources was tackled recently in the scientific world and their interaction was explained in brevity in the previous section. Also the necessity of modeling the future scenarios, and developing a picture of our recent future state was anticipated. The modeling in WRM has been an occupation of the engineers and scientists time ago and it goes forward with the improvement of the technology. The same stands for the global climate/circulation models and predicting the future climate change scenarios. In fact very powerful models were developed in USA EPA(Environmental Protection Agency), Rossby Institute, and other institutions as well as, in Europe, Stcholom Institute for Environment came out with WEAP(Water Evaluation And Planning), also EEA(European Environmental Agency) and EC(European Commission) are developing similar kind of projects. Considering the agriculture, USDA developed SWAT (Arnold and Fohrer, 2005), a river basin scaled model for quantifying the impact of different management practices including the irrigation and agriculture. Than FAOs Aquacrop simulates yield response to water of herbaceous crops, and is particularly suited to address conditions where water is a key limiting factor in crop production. In relation, Politecnico di Milano based on these world trends, intensively is working on optimizing the water resources usage especially in Northern Italy, thus in this thesis we are going to use some of those models and approaches. Or more precisely the distributed-parameter model of Muzza agricultural district that was recently adapted and developed, having AquaCrop and SWAT models as a background. This model will be called *District Model*, and if coupled with the simple lake regulation model, *LakeDistrict model*, or irrigation model of Muzza. I.e Galelli

et al.,2008 developed a meta model that reduces the states in the design problem and makes the SDP useful for the distributed parameter. Later on there are some other studies about developing the district model, adding the nitrogen cycle and so on. Furthermore, until now most of the studies have focused on assessing the climate impact only on a hydrological basin scale (e.g. Jasper et al., 2004;Bronstert et al., 2007; Groves et al., 2008; Abbaspour et al., 2009). Later on there are some studies that attempt to extend the quantification towards socio-economic and nature systems combined, e.g. hydropower production(Schaeffi et al., 2007; Christensen and Lettenmaier,2007), floods, ecosystem and agriculture (Hingray et al.,2007). Nevertheless, the framework is here, the models are partially developed, the future scenarios are published on free on-line servers. The only problem is that we can not model the nature as it is, neither in can be accurately predicted. Therefore the scientists and the engineers make reasonable and rational assumptions in order to deal with current technology, and to design a trajectory for the future socio-economic behavior. As it was mentioned in the introduction the need for increasing stakeholder participation in this type of analysis is well-recognized. For instance EC has already published the guides about adaptive water resources management.

The assessment of the climate impact on a water-related activities is very complex because of the following reasons:

- The analysis must account for the true expectations and needs of the water users, defining quantitative indicators requires a long and complex process of knowledge elicitation from experts and stakeholders representatives (Soncini-Sessa et al., 2007).
- The management policy of the system must be defined. The modeling of the management is sensitive during the time due to the changed meteo-hydrological conditions.
- And the associate uncertainty affection through the entire procedure.

It slowly approaches towards one of the main goals of this thesis, the climate change UNCERTAINTY. The evolution of socio-economic drivers, e.g. population growth and economic and technological development, cannot be exactly predicted. For given driver scenario, the response of the climate and water system is estimated by simulation models

that inevitably exhibit structural and parameter errors. All these uncertainties are propagated and possibly amplified in the modeling chain from the global climate to the impact assessment (Schaeffli et al., 2007). Uncertainty analysis must therefore be an integral part of any impact study. Since taking into account all the uncertainty sources simultaneously requires a huge computational effort, impact studies usually analyze only the most relevant sources at the temporal and spatial scale of interest (Anghileri 2014a)[1]. There are few studies in recent times that considers quantification of the climate change, but usually they are in smaller domain and they do not consider the PIP approach.

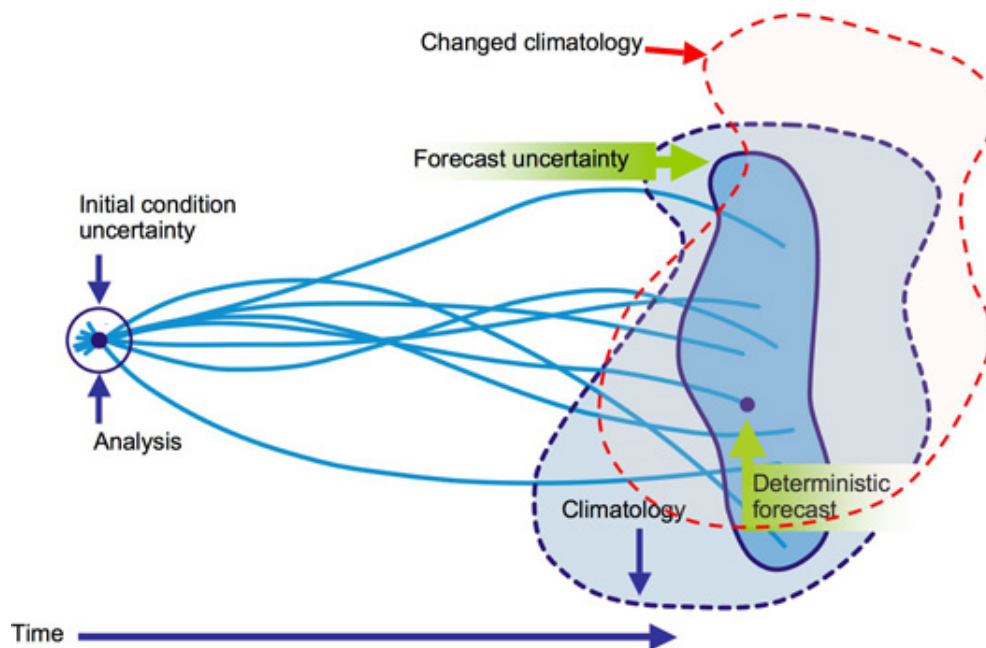


FIGURE 1.1: Dealing with uncertainty.

This thesis is dedicated to give an idea about robust future climate change decision making in water resources management including the multi-agent based, distributed decision process of the farmers as a feedback of the closed loop with the water manager DM. In fact the main objective is to provide a comprehensive, reproducible picture of the potential impact of the climate change, thus to help the planning procedure of the water system. It is of fundamental importance to increase public awareness, support water resource planners and promote stakeholders participation in decision-making process. Moreover the assessment is done using the newest climate and socioeconomic future scenarios. Namely the previous studies (e.g. Anghileri2014a, Arnell (2004),D'equ'e et al. (2007)) used the GCM outputs published from the fourth IPCC assessment report

(AR4). Here the objective is to use the newest EUROCORDEX data, regionally down-scaled data, and perform the system performances. Moreover the objective ramifies into few facts and drawbacks about the CC analysis.

Firstly the negative impact from the temperature rise and heavy precipitation is pretty intuitive, so the natural variability affects the impact by default. Also one can bear in mind that we will use a finite time horizon (of observed data and CC scenarios) and it will affect the convergence of the results. Another thing is that the optimization procedure is quite exhaustive and it requires a high computer performances in order to have sufficient outputs.

Another objective is to show that any kind of adaptive strategy will improve the system performance. Anyhow the gap between the future water supply and the current water demand remains large, which means that another planning actions will be required, like crop rotation, change of the irrigation system, new fertilizers and so on. The approach is demonstrated by application to Lake Como basin, Italy, a complex water system in the Southern Alpine region. Briefly, it is composed of an irrigation fed agricultural district downstream of the lake, which is one of the largest irrigated area in Europe, as well as other interests that play active role like preventing floods on the lake shores and some suggestive like preserving ecosystems both in the lake and along the river, in this case only counting the minimum environmental flow.

The complexity and computational burden of circulation model do not allow for simulation at the local spatial scale where the impacts on water-related activities must be estimated. To fill the gap between global and local scale, many methods were developed to downscale General Circulation Model (GCM) and Regional Circulation Model (RCM) projections. Therefore EUROCORDEX assembles the outputs of the dynamical downscaling of many institutes and presents them in different resolution, format and intensity. The latest downscaling processes are synthesizing the state of art about producing different climate variables out of the future emissions scenarios, this time given as RCP (representative Concentration pathways). This new approach offers more realistic information of the climate variables developed in parallel with the socio-economics story lines, new updated historical data and adaptive measures taken. In details will be explained in the chapter 3.

The state of art implies the combination of the PIP procedure and the newest AR5 pathways, which leads to cross-correlation between the socio-economics aspect included in both approaches, e.g the economic trends, population, policy change.

1.2.1 Integrated and Participatory Water Resources Management

Recalling the facts stated in the first section and based on the recent articles and reports mentioned in the previous section, short introduction into IPWRM seems to be rather necessary.

Water is a key driver of economic and social development while it also has a basic function in maintaining the integrity of the natural environment. However water is only one of a number of vital natural resources and it is imperative that water issues are not considered in isolation. Managers, or the regulators, have to make difficult decisions on water allocation. The natural systems are also subject to anthropic pressure. More and more they have to apportion diminishing supplies between ever-increasing demands. Drivers such as demographic and climatic changes further increase the stress on water resources. The traditional fragmented approach is no longer viable and a more holistic approach to water management is essential. This is the rationale for the Integrated Water Resources Management (IWRM) approach that has now been accepted internationally as the way forward for efficient, equitable and sustainable development and management of the world's limited water resources and for coping with conflicting demands.

This approach draws back many difficulties, since we deal with a project in which we have many individuals involved, we need governmental agencies cooperation and authorization, we talk about procedure described in a public realm. In order to achieve good planning and good management it is absolutely necessary to overcome these difficulties by conducting a *participatory, integrated and rational decision making process*.

From the previous section can define that the complexity of decision making is being related with the climate change in an unavoidable way. Therefore it arises the difficulty of water management decision making, mostly because of the *uncertainty* of the climate change. Water management planners are facing considerable uncertainties on future demand and availability of water. Climate change and its potential hydrological effects are increasingly contributing to this *uncertainty*. The Fifth Assessment (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013) states that an increasing concentration of greenhouse gases in the atmosphere is likely to cause an increase of the surface temperature, but compared to the previous report, the lower bounds for the sensitivity of the climate system to emissions were slightly lowered, though the projections for global mean temperature rise (compared to pre-industrial levels) by 2100 exceeded

1.5 °C in all scenarios. This will lead to a more vigorous hydrological cycle, with changes in precipitation and evapotranspiration rates regionally variable. These changes will in turn affect water availability and runoff and thus may affect the discharge regime. The necessity of participatory planning is straightforward, since the socioeconomic impact is one of the major drivers of the uncertainty also in predicting future climate scenarios. The effective use of climate information can be impacted by the degree of collaboration between climatologists, hydrologists, and the decision-makers (DM). The paradigm of IPWRM requires adoption of Multi-Objective Decision Support System (MODSS), indeed it is a crossroad of the three worlds participant mentioned above, world of sciences, world of methodologies and naturally the world of information technologies in order to produce applicable software, and revive it in materialistic sense. The goal of DM procedure is to reach an agreement that is acceptable to all the actors of the IPWRM. The PIP procedure presented below is the conceptual map of modules of the DM procedure MODOSS. PIP is also an approach to overcome the difficulties met in the DM process and it assumes participatory process that will increase the public awareness, will also integrate all the actors and rationally will deliver the final decision/compromise.

PIP A lot of case studies and applications all over the world proved that a bottom-up, integrated and participatory decision-making process is much more effective than the old top-down approach. In this direction, the Politecnico di Milano developed in recent years the Participatory and Integrated Procedure (PIP), a holistic approach to address Multi-Objective optimization problems aimed at reaching an agreement – best compromise alternative – that is acceptable to all the participants, being the result of a negotiation among all of them. Specifically, the main actors in this process are:

the *Stakeholders*, people, institutions, companies, organizations or agencies that will experience some effects of the decisions to be taken. In our case the farmers, the shore dwellers, water manager;

the *Decision Maker*, the person or authority that is in charge of selecting the best compromise alternative among all the possible ones that the procedure develops according to all the stakeholder's interests. Consequently the farmers are their own DM, the lake citizens are represented by an authorized institution and the water decision maker;

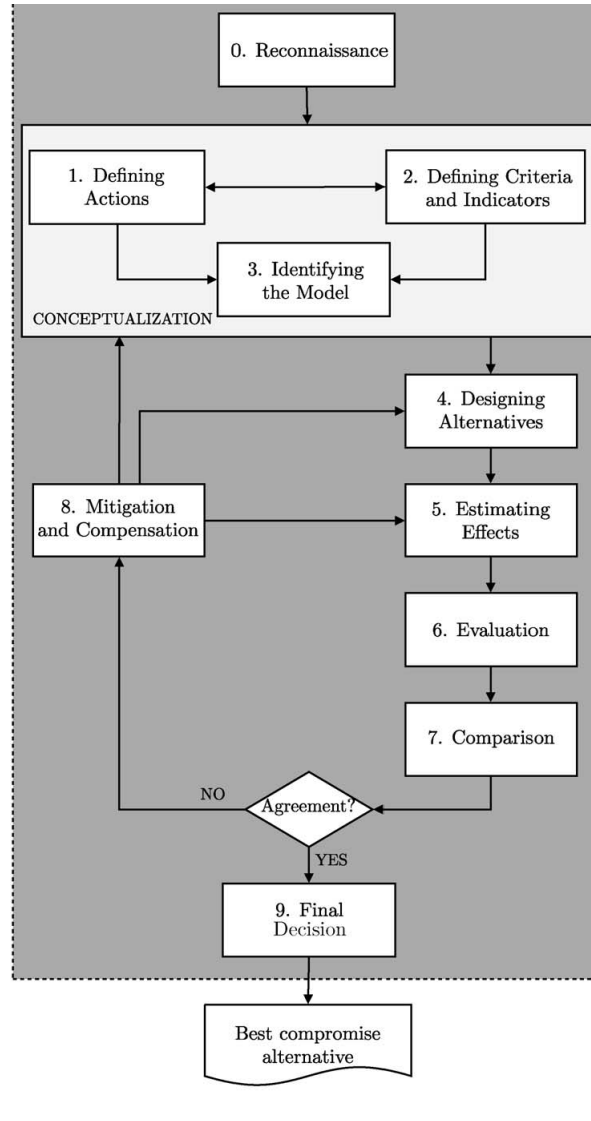


FIGURE 1.2: PIP phases

the *Analyst*, the person or authority that conducts studies, draws up the Project or Plan together with the stakeholders, so that the final result cannot be questioned.

1.2.2 Novelities

Coherently with Anghileri2014a paper[2] about the climate impact on the hydro-power and the irrigation, the novelties of this study are:

- Construction of future time projections, using state of art GCM/RCM outputs, under the last update of the emission/concentration pathways(called RCPs, IPCC, AR5).

- The quantification of the impacts is based on a set of performance indicators defined together with the stakeholders representatives, thus explicitly taking into account the water users preferences;
- The multi-objective nature of the management problem is fully preserved by simulating a set of Pareto optimal management policies under different climatic scenarios, which allows for evaluating not only variations in the indicator values but also tradeoffs among conflicting objectives;
- Uncertainty analysis results in deriving confidence bounds around the simulated Pareto frontiers and defining the major source of uncertainty regarding the water management and CC scenarios.
- Defining qualitative, performance characteristics of different up-to-date GCM/RCM future scenarios, that are aimed to facilitate the future studies related with the CC impact to the water resources management.

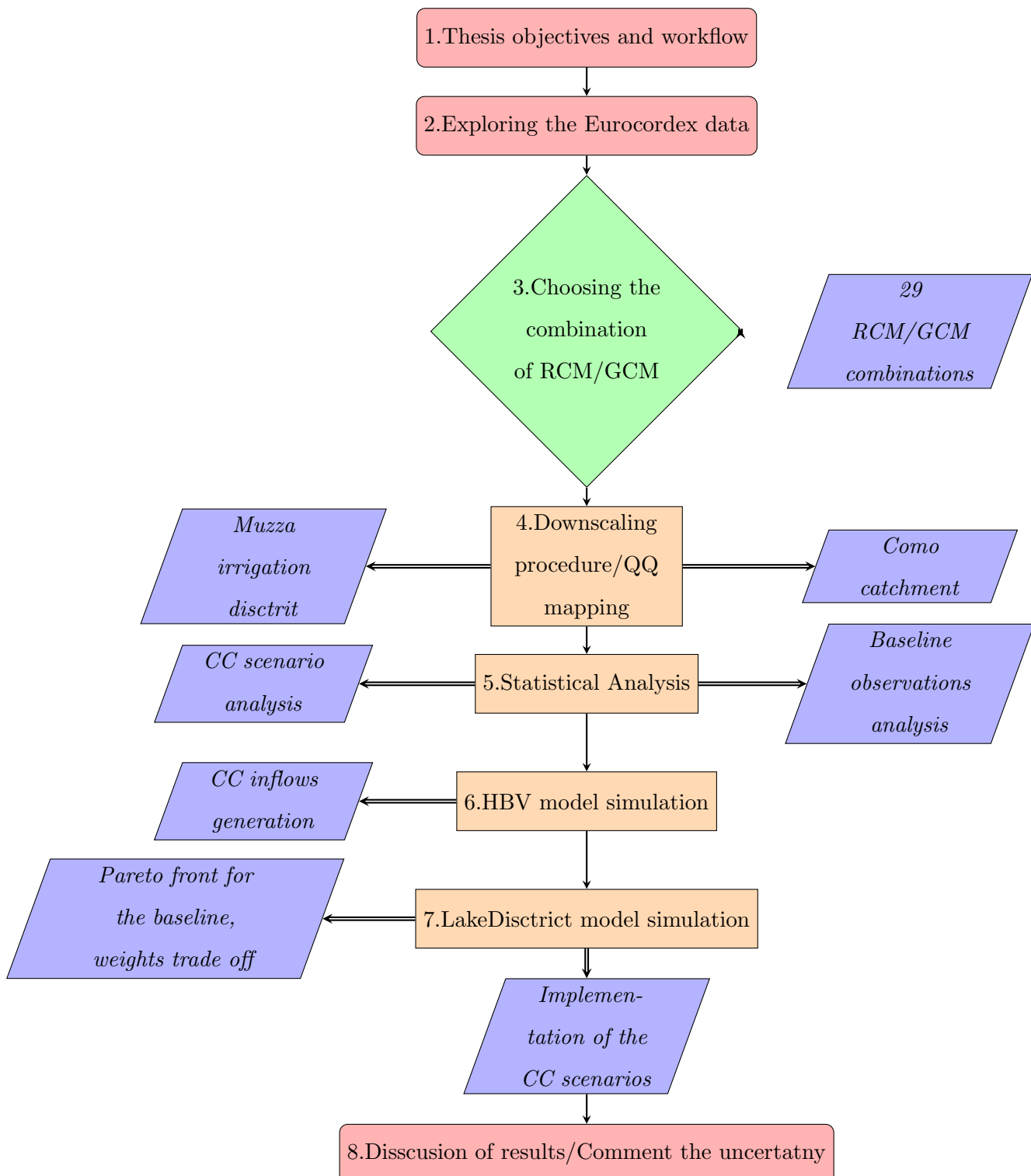
1.2.3 Challenge

The scientific challenge is not to forecast the future management policy of the system, but to give global robust understanding of the climate change impact towards the farmer's decision and regulation policy. Indeed it is quite inconvenient and very improbable to define the water prices, the policy changes, subsidies, crop market economy, except it is a very recent future. Moreover implementing the new climate variables using MAS, having the farmers and the lake operator as active agents, aggregating their interests and proposing an future scenario that will help the planners to produce new adaptive polices, it is a challenge by itself, not just in scientific point of view, hence more in a pragmatic way.

1.3 Thesis structure

In the context of this thesis we offer the in the first chapter. Than in the second we explain in details the study site and the current performance of the system, including the recent climate statistics. In the third chapter we deal with the methodology and models used to simulate the current and the future situation. The results and the

comparison is given in the fourth chapter, and the discussion, conclusions and future scientific questions are given in the fifth chapter.



Chapter 2

STUDY SITE

2.1 Site Description

In the introduction we gave the main focus of this study and in that sense the spatial domain was anticipated. Located in one of the richest regions in Italy, Lombardy, we are going to deal with two important areas which are connected through the river called Adda. The first of interest is Lake Como and its catchment. Lake Como is the third largest lake in Italy and one of the deepest in Europe with more than 400m depth. Lake Como is very famous touristic attraction in Italy, but beside that it has major role in the water supply of the entire area. In 1946, with the construction of a regulation dam at the lake outlet, the lake was transformed into a reservoir. Its license act states that the lake regulator can freely choose the release when the lake level is between 0.50 and 1.30 mat the Malgrate hydrometric station (an interval called regulation range), while (s)he has to open the dam gates completely when the level exceeds 1.30 m and release not more than the inflow when the level equals -0.50 m(Galelli, Gandolfi, Soncini-Sessa, Agostani, 2010)[3]. It is now a natural regulated lake with a surface area of 145 km² and an active storage of 260 Mm³. The Lake Influent and effluent is Adda river, which river serves eight run-of-river hydroelectric power plants, with a total installed capacity of 92MW, and supplies a dense network of irrigation canals that supports five irrigation districts with a total surface of 1400 Km², where maize and permanent grass are the most common and economically significant crops. Among those irrigated agricultural district, one of the biggest is the Muzza Bassa Lodigiana district. Logically, this district is served by the Adda River, located south-east of the city of Milan in the Pianura



FIGURE 2.1: Lombardy (System allocation).

Padana region (B.1). It has an area of about 700 km² and irrigation is practiced with the border method (or free-surface flooding). Major crops are cereals (especially corn) and permanent grass. The irrigation supply is provided by the Muzza main canal, which originates from the River Adda, and is hence controlled by the regulation of the Lake Como.

The network of gravity flow, irrigation canals is characterized by a high inertia, which does not permit one to change the diverted flow rapidly and to follow the fast-varying water demand. Thus, the current canal regulation tends to track an "a priori" given reference trajectory. This fact has a significant consequence if we note that that during the irrigation season the total water demand of the irrigation districts located downstream from all the power plants is larger than the hydropower water demand: by satisfying the first, the second, too, is satisfied, thus removing competition between farmers and hydropower companies in the irrigation season. During the winter, their competition for the autumn storage has for a long time been solved by a *gentleman's agreement*: the regulation is in favor of hydropower plants. From these considerations it suggests

that, currently, only two objectives have to be considered in the policy design: flood reduction and downstream water supply. Current regulation policies are optimized on the basis of a normative demand of downstream irrigation districts, namely with the average demand of the last decades. But this is not necessarily even close to the expected one for the following year. Every year, in fact, farmer's decision about the allocation of land to each crop typology varies according to market demands, expected prices and many other factors hence, along with it, the water demand changes year by year as well. In the last decades, a series of significant droughts have been observed which arose the concern in water savings and attention has been paid to the water losses produced when the diverted flow is higher than the water demand of the irrigation districts (e.g. during precipitation events). These losses could be decreased by a modified plug-flow model, assuming that flow can be varied, with in some limits, almost instantaneously and thus be quickly adapted to the fast-varying irrigation demand (Galelli et al., 2010)[1]. In addition, we will assume that the transport time is null, since (considering the size of the downstream area) the on-demand canal regulation implies that the time required for a released volume to reach the last irrigable field (less than 10 h) is lower than the decision time-step of the management problem (1 day). These two assumptions together imply that the volume is delivered to the crops instantaneously, and therefore that the modeling effort can be concentrated on the irrigation district only.

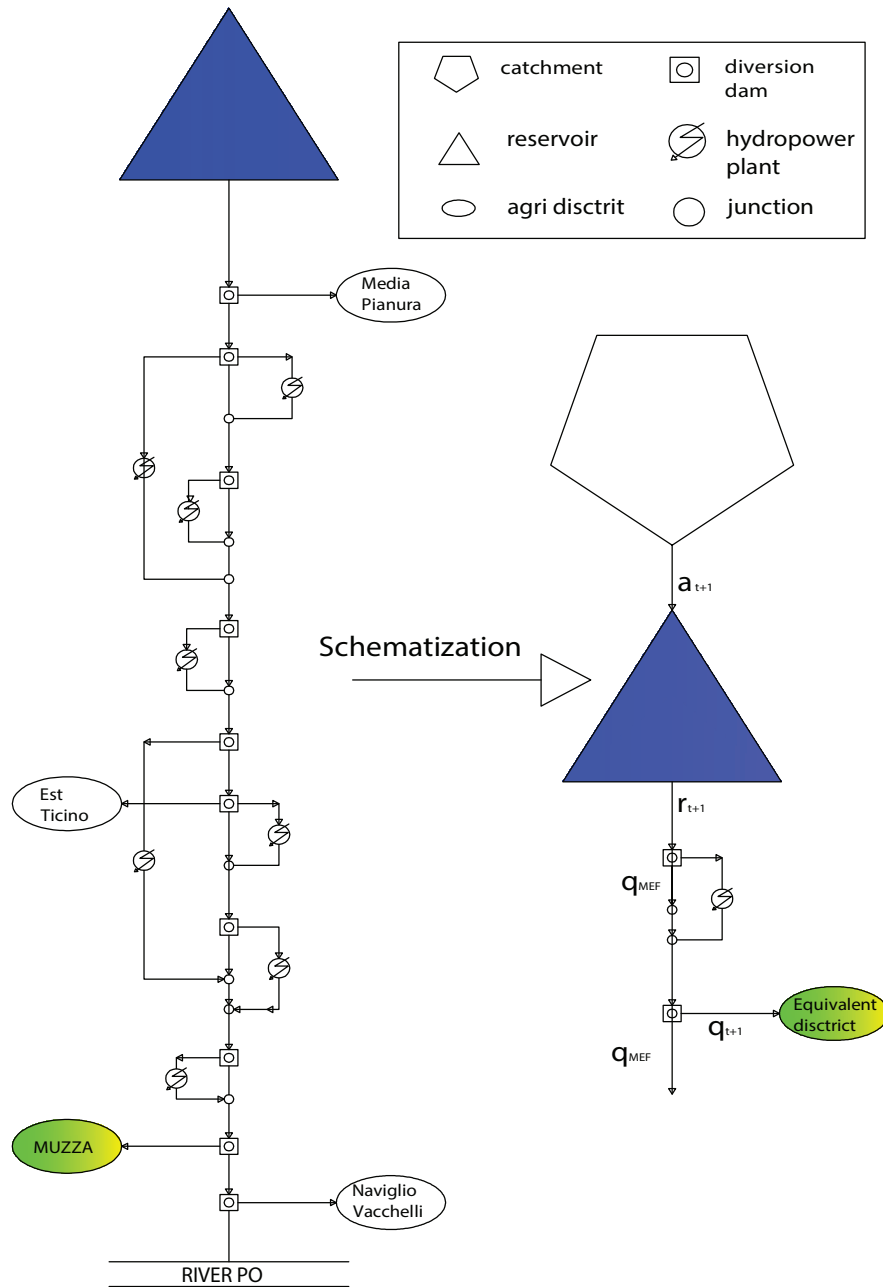


FIGURE 2.2: Simplification of the down stream system.

Nevertheless a distributed-parameter model is available only for the Muzza district. Indeed, Muzza is the largest of the five irrigation districts and, with an area of 700 km², covers about 25% of the total irrigated surface and generates almost half of the total water demand. Since this district well represents the agricultural and irrigation practices of the whole irrigated area, we assume that the total water demand of the five districts can be computed by up-scaling the Muzza water demand with a suitable actor. From Fig. 2.2 it is apparent that the withdrawal points of some irrigation districts

are interposed between power plants. However, these districts total only 30% of the irrigated area, so that we decided to further simplify the model by assuming that all the districts are located downstream of the hydropower plants. With this latter assumption the Lake Como system can be schematized as in Fig2.2, where the equivalent power plant represents the cascade of all the power plants and the equivalent irrigation district is the union of all the irrigation districts. Anyway this is not of central importance for our study since as it is mentioned we cope only with irrigation and floods assuming that the hydropower is not in conflict with these two.

2.2 Hydro-climatic behavior

Como catchment area is in the middle of European continent, therefore it is characterized by the typical Alpine hydrological/ pluviometric regime with low discharge in winter and summer and high in late spring and autumn. It is fed by a 4500 km² catchment, which produces an inflow process, averaging 4.73 Gm³/year, which is scarce in winter and summer, and peaks in late spring and autumn. The two inflow peaks are mirrored in two storage peaks: one in late spring and one in autumn. It is noticeable from figure 2.3 that the catchment area is spread in Switzerland and Italy as well. Therefore there should be good cooperation between Swiss and Italian meteo station if we want consistent data.

The following context will briefly show you the hydro-meteorological behaviors in Como catchment. To be consistent with the modeling procedure and optimization, the information presented will consider only the years used for calibration and running the models.

Precipitation pattern

The precipitation data will be represented in 3 different ways, as an annual sum of the period of interest from April until December, the cumulative distribution, and the dry spells. As a matter of comparison the representation of the first two statistics is given together with the temperature statistics (fig2.5). Actually here we deal with real data and observations, so the data can be given in a representation of hydrograph (fig2.7), which in fact is the most common way.

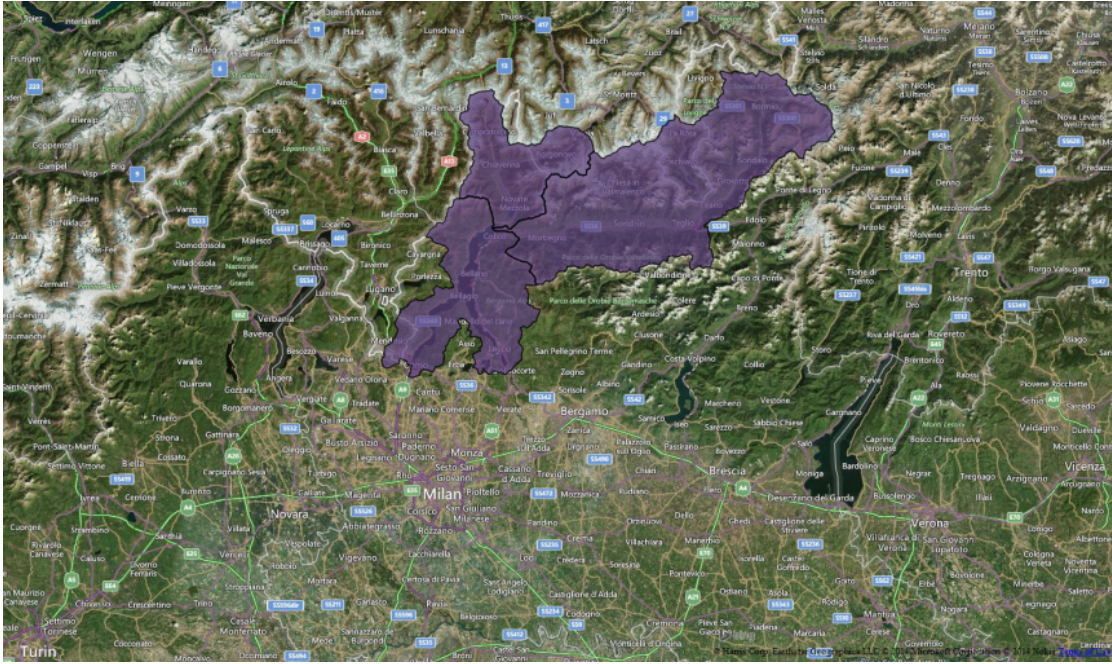


FIGURE 2.3: Como catchment area

1. *Annual sum of the precipitation.* The purpose of this raster presentation (the first subplot of fig. 2.5) is to make the comparison taking the annual sum of precipitation in the period of 1st of April until 1st of September, which assumes the top cultivating crop season. The following graph 2.5 give us information, scaling from blue to red as wet to dry years, given in subplots with the temperature patterns in order to show a visual correlation between. Indeed, this raster plots are given as consistency with the raster plots for the CC scenarios in the Ch.4. The aim of this statistics is to see how dry the year was, and to decide if we deal with a dry or wet year. Knowing this we can have some preliminary opinion about the water demand and the possible floods, caused by the lake level increase. From this raster representation we can notice that we deal with pretty dry period with precipitation between 300-600 mm for the period of interests. For comparison the annual precipitation in the dry regions in Africa is around 200 mm.

$$Pr_j = \sum_{i=1}^j pr_i \quad (2.1)$$

2. *The cumulative distribution.* As it is known in probability theory and statistics, the cumulative distribution function (CDF), or just distribution function,

describes the probability that a real-valued variable Pr (in our case the data array from the rainfall observation) with a given probability distribution will be found to have a value less than or equal to pr_i . The cumulative distribution function is given by:

$$CDF(x) = P(Pr < x) \quad (2.2)$$

The aim of this statistics is to show how often the heavy rain events are happening, as well as the dry ones.

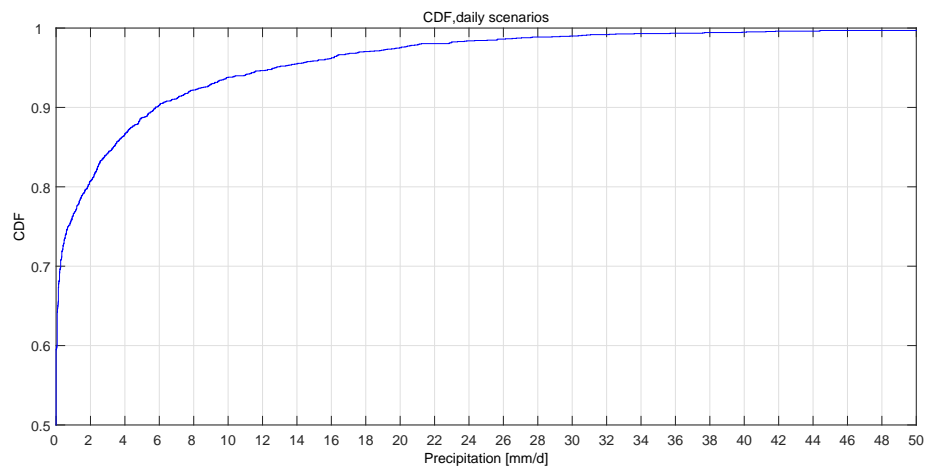
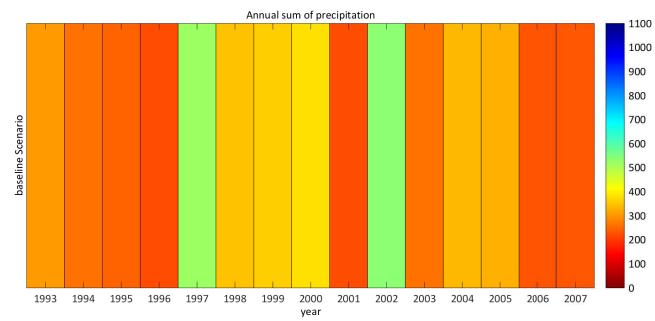
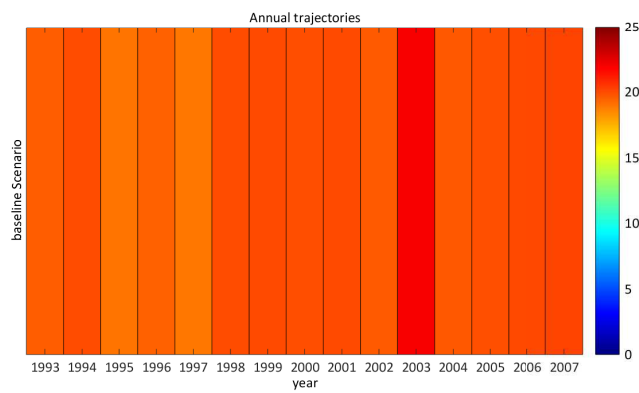


FIGURE 2.4: CDF of the precipitation events

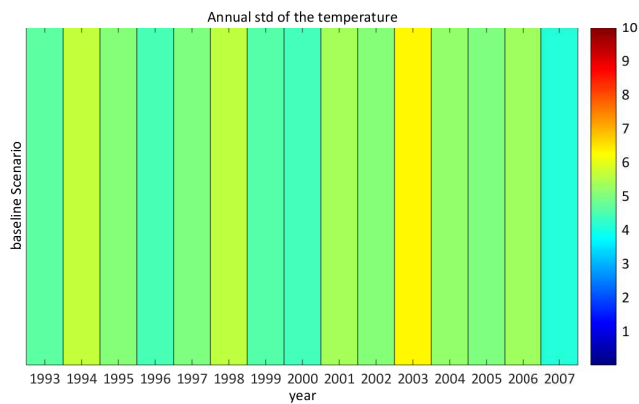
The CDF(fig.2.4) clearly provides an information that we deal with quite dry period where 70% of the days in the period of interest we have little rainfall. It should be noticed, however, that the CDF plot here is based on the spatial average values, which might underestimate the actual values measured at each stations.



(A) Total annual Precipitation mm/d



(B) Mean annual temperature



(c) STD of the temperature

FIGURE 2.5: General Baseline Statistics for the irrigation period (apr-sep)

3. *The dry spells.* Since we deal with dry years it is useful to see how many consecutive days we have no precipitation. Dry spell is a period of days when the precipitation is under certain amount. In our case it is important

for the irrigation district of Muzza region in order to locate sequences of days that can harm the agricultural cultivation, and in that sense to perform mitigation, or optimization of the water supply management policy. There are few indicators associated with the dry spells. Different authors used different threshold to define dry spell. The most common one, adopted by many meteorological association around the world is: *precipitation threshold below 1mm/day, counting 6 consecutive days.*

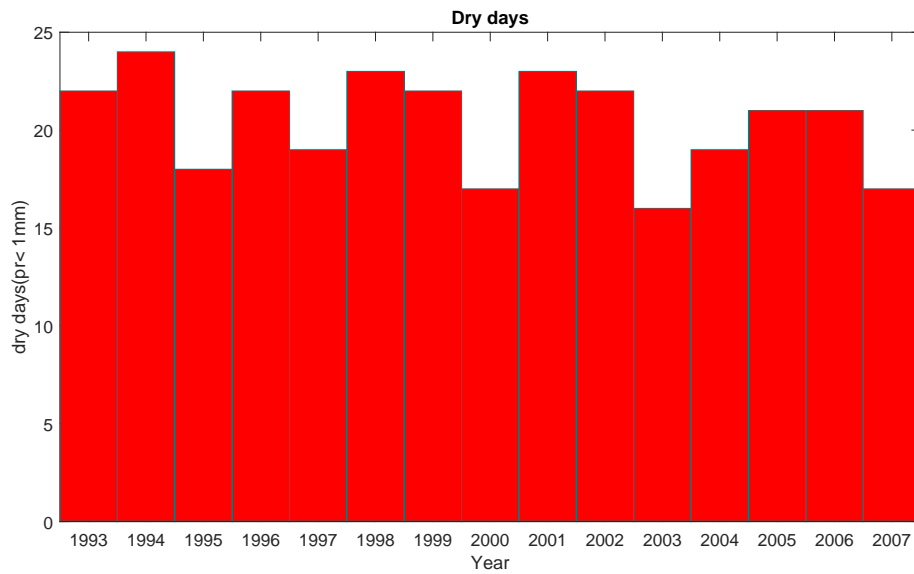


FIGURE 2.6: Number of Dry days during the simulation horizon in Muzza region

TABLE 2.1: Number of dry spells

Number of dry spells								
1999	2000	2001	2002	2003	2004	2005	2006	2007
8	9	8	11	9	8	8	6	8

It can be noticed from 2.2) that the number of spells per year are not negligible and that the number of in average 8 dry spells per year is quite significant and the irrigation in this period is more than important for fruitful harvest. The number of dry days, regarding the cultivating period also suggests that the dry days without precipitation might cause significant damages to the agriculture.

4. *The hydro-graph.* As it was aforementioned, we offer a brief preview of the hydro-graph, accompanied by the rainfall in order to show the catchment

retardation factor or the lags between the peaks. This will be just used as representation of the daily rainfall (5475days=15years). It can be noticed

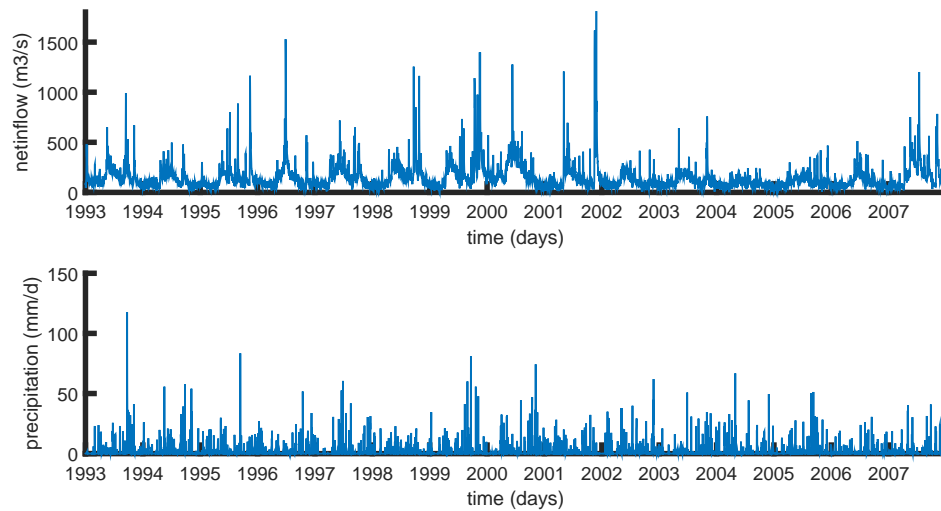


FIGURE 2.7: Representation of the precipitation and the inflow in Como catchment area

that the peak areal precipitation are happening in early autumn or spring, either the inflow wave comes with lag of few days later. In case we have intensive snow falls like in some years(), the inflow intensity is noticeably higher than usual.

Temperature pattern

The local temperature meteorological statistics review will be focused on defining the hot years, trying to understand the heat waves and the variation or the deviation during the plant breeding period or the irrigation period.

1. *Mean temperature.* This simple statistics stands for the average daily surface temperature during the irrigation period. Therefore the raster plots 2.5 clearly give us information that we deal with hot period with sultry summers that increase the average temperature. This implies that irrigation has to be proper and regular if we do not want to cause drying of crops or significantly lower yield.
2. *Standard deviation (STD).* STD is a statistics that shows how the values from the sample are varying around the mean value. In other words the STD give us information about the distribution of the mean temperatures, how clustered are they around the annual mean, in this case. *It should be mentioned*

that both statistics are done for the cultivating, irrigating stress period. The results perform not a significant deviation of the daily temperatures, which means that during the irrigation period the average temperature do not vary significantly from the beginning of the period till the end. This is a good news for the farmers, since they do not have to be afraid of late spring frosting, or of summer burning. However we should check the heatwaves for more suitable information about the later.

3. *Heatwaves.* Heatwaves are frequently defined as a period of unusually or exceptionally hot weather. Extreme events typically occur in mid-summer, although less intense heatwaves are also experienced during spring and early autumn. Or, more precise explanation taken from WMO: *“Descending, drying air within an anticyclone results in dry and warming air under clear skies. These clear skies allow radiative heating of the underlying surface during the daytime, which over land adiabatically exchanges heat into the overlying air. What would be a normal warming cycle ahead of the next cool air mass change can become stagnated when a slow-moving anticyclone prolongs the heating cycle, occasionally producing a heatwave.”* The literature offer different definition and values for the threshold, but we stick to the most common ones, adopted in the middle Europe we define a heat wave as: 5 consecutive days when the average surface temperature higher than 25 C. Not to induce a confusion in some literature (CMCC Climate Service) heat wave is defined by the number of consecutive days when the maximum temperature exceeds the seasonal average temperature by x degrees (e.g. 5 higher than the average temperature). Nevertheless our data does not contain max temperature, only average so we will recall the previous definition.

TABLE 2.2: Number of heatwaves

Number of heatwaves								
1999	2000	2001	2002	2003	2004	2005	2006	2007
6	3	5	5	2	3	5	3	5

This is additional information about the possibility of droughts and gives an additional suggestion for the water manager about his release decisions for

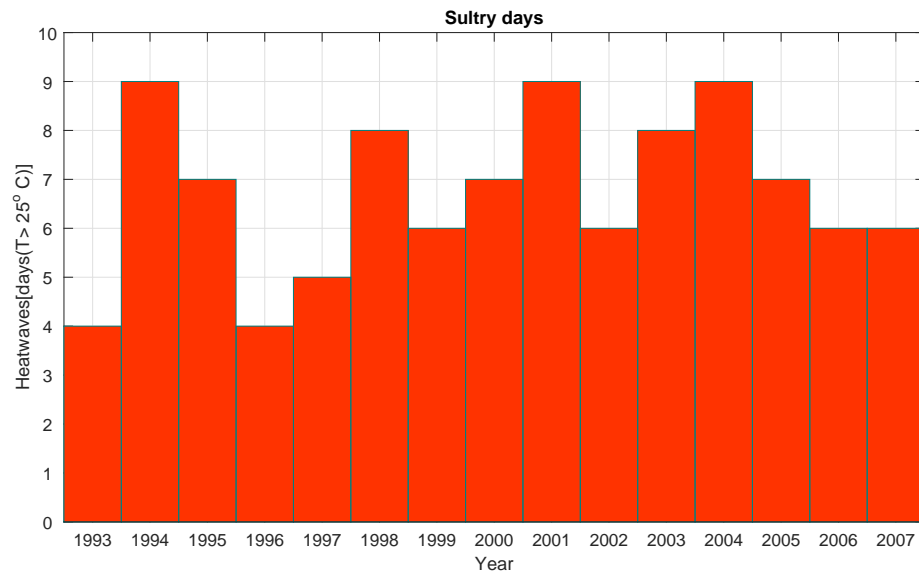


FIGURE 2.8: Number of sultry days

the irrigation. The table and the graph in fact say that there is not peculiar treat to the crops due to the heatwaves, and the yield is not endangered. Furthermore, maybe more attention has to be aimed towards the dry spells. The famous heat wave in Europe in 2003 in fact did not influence a lot giving just 2 heat waves. However this is just assumption since we deal just with average temperature, which is not reliable enough to present the real situation.

Climatic graph

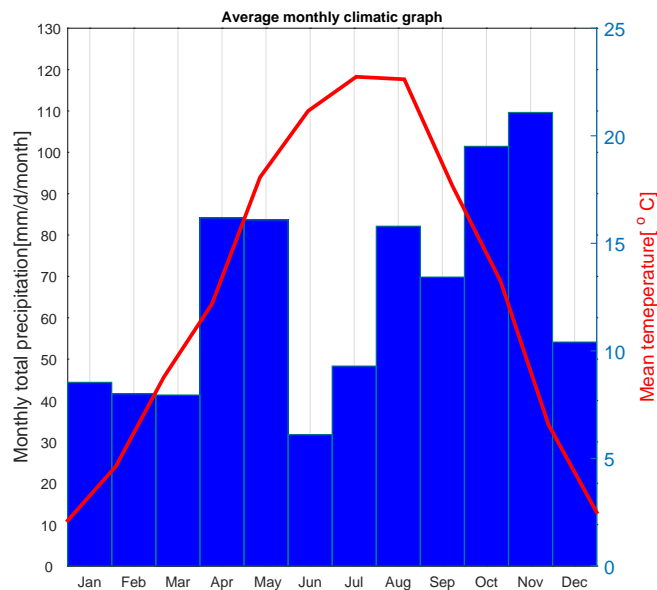


FIGURE 2.9: Climatic graph(monthly precipitation and temperature)

A climatic graph shows the climate (temperature and precipitation) of a particular area over the period of a year. In this case it is a representation of the average monthly temperature through the year, and total monthly precipitation, both considered as a mean rough the baseline horizon. Climatic graphs show this data by using a line graph to represent the monthly temperatures and a column graph to show the monthly precipitation. Precipitation is recorded as a bar graph. The temperature is recorded in the form of a line graph. This graph 2.9 give us a holistic perception about the monthly climatic conditions, offering an information that can contribute in the explanation of the water manager monthly behavior.

Inflow trends

This is the last statistics performed and it shows the trends of the inflows. Here we will use the MASH (Moving average over Shifting Horizon). This statistics give use opportunity to look and detect the interannual and seasonal variability at once¹. Since we deal with a horizon of 15 years, intuitively we are choosing the parameters as $Y=10$, or 10 years of horizon, and $w=10$, 10 days moving window. The selection of 10 years moving horizon is due to the interannual variability which

¹it will be explained in details in Ch.4.

tends to prevail, for shorter horizons, in comparison with the seasonality. Later we will show a comparison with inflows produced by HBV (rain fall/runoff model) for the CC simulation horizon (2090-2100).

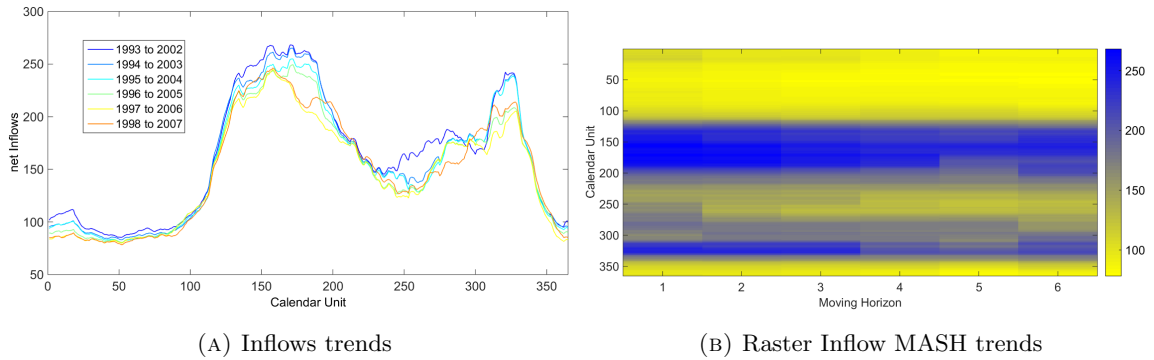


FIGURE 2.10: Baseline MASH plots

Two presented graphs 2.10 show very clearly the trends of the inflows. In that context we can notice general decreasing of the net inflow in the lake through the entire horizon. There is no seasonal peak shifting, but the peak reduction is quite emphasized through the years, thus the maximum peak reduced and the minimum peak is diminished as well, trends of lower stress periods and flatter inflow graphs area performed during the horizon.

2.3 Socio - Economic Components

Referring to the thesis goal and the stakeholders we can clearly distinguish and define the socio-economic impact of our hydraulic scheme. Therefore, recalling the PIP procedure here we are moving from Reconnaissance to defining actions and defining criteria. Having the farmers and the citizens of Como Lake shore as primary stakeholders, and DMs on the other side, obviously we deal with social and economic problems. The socio economic aspects can be explained starting with defining the interests of all stakeholders. Thus, we have the farmers and their crop production activities, the municipalities or the citizens affected from the floods and Como lake water regulator. This study consists of integration of all this planning problems and allow significant improvement of the crop production, reduction of water wastage and lower damage to the shore towns.

2.3.1 Problem formulation

2.3.1.1 Farmers Problem

The region of Muzza consists of 66 farmers, or farmers families, that are dealing with different types of cultivation in order to increase their revenue. Naturally every single entrepreneur expects maximum incomes as result of his product sale. Gross farm income includes cash receipts from the sale of farm products, government payments arising from farm program participation, the value of fuel, feed, fertilizer, seed and other inputs consumed on the farm, and the rental value of farmland and dwellings. Farmers often are able to enhance their income by using futures and/or production contracts to achieve a higher selling price than would be available if a crop was sold at the time it was harvested. Often, production contracts require the seller (the farmer) to achieve certain levels of quality and/or quantity in order to qualify for a premium selling price. Also there is additional issue if the farmer has a multi-farming facilities, thus he uses part of the planting production in order to feed the livestock, than he deals with the cattle's manure and so on. Furthermore, detailed economic balance has to take into account the so called shadow prices. In general the agricultural activities production is a complex business, requiring many skills (such as biology, agronomy, mechanics, and marketing) and covering a variety of operations throughout the year. However for the sake of simplicity, the above given scenarios and assumptions will be discarded in our case, and simply the farmers final yield will be defined as product of the biomass produced and the price of the crops. The former is influenced by different factors, among which the different crops' agronomic features, the climatic conditions and the actual water availability for irrigation during the crop growth period; the latter depends on the market price of each specific crop, and can be considered, in a naive way, as a deterministic scenario. In reference each year the price is changing due to different economic, social or politic reasons. In this direction, the main assumption In this work is that farmers periodically go through a complex decision-making process which generates their production choices on the basis of their knowledge about the different crops' productivity and agronomic properties, the expected amount of water that will be delivered from the upstream reservoir, the existing climatic conditions (as also suggested by Mejias et al. (2003)

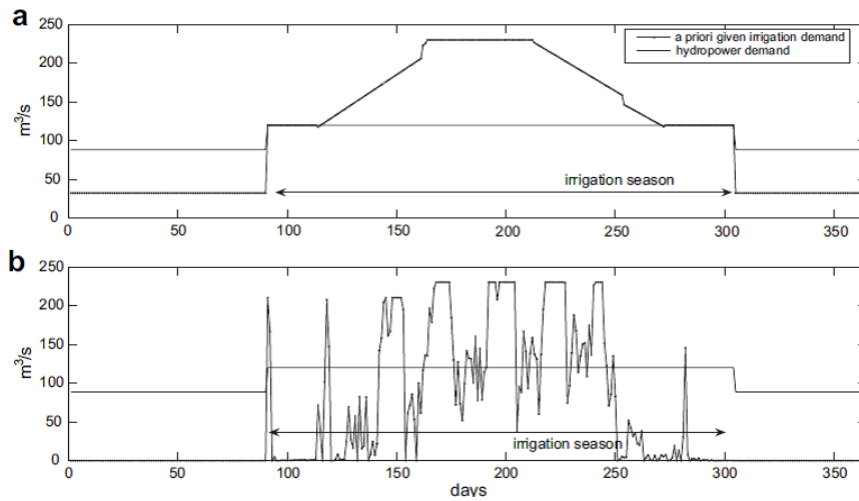


FIGURE 2.11: Hydro-power and irrigation a priori water demand, one of the patterns

Nevertheless there are many exogenous factors dependent on socio-economics context that influence the procedure of the system performance. We will give a short review towards the water prices and the crop market, and not going beyond the scope of this dissertation.

2.3.1.2 Water prices and Crop market

The irrigation sector is the largest user of global water resources. Commonly, capital investments are needed to move water from the natural water bodies to the irrigation fields. The long-term development and building of irrigation projects may require that governments plan, finance and implement them. In many cases, government agencies also get involved in running and managing the irrigation schemes. Tariffs are charged only when the scheme becomes operative, although provisions are made to recoup part of the financial and amortisation costs and cover the entire OM costs.

The water distribution system in Italy is mainly managed by “Reclamation and Irrigation Boards” (RIB), that formally speaking, are public law associations of asset owners that control the management and distribution of water resources over a certain area. Water use regulation is based on a complex system of rights, often developed since ancient times. Water pricing usually works through surface based charges that are aimed to cover RIB operational costs (Bazzani, G. M., S. Di Pasquale, V. Gallerani, and D. Viaggi (2004)[4], Irrigated agriculture in Italy and water regulation under the European

Union water framework directive. In reference the application of Water Frame Directive (WFD) is now in action and brings many changes and adaptations. WFD identifies some major economic criteria for all countries make a reformulation of the current policy considering its elasticity and sensitivity to the agricultural water prices. The WFD also recommends pricing as an instrument for reducing water use and water pollution. The final price should take into account both the full cost recovery and incentive considerations in order to lead to the best social use of water. It can be seen that the water prices are quite hard predicting scenario, maybe impossible if we consider more than 10 years future influence. The food price spike spanning the 07-08 period seems to be affected also by a macroeconomic scenario influencing the world commodity markets as the rapid growth in food demand due to rise in GDP, the international financial crisis, and growing influence of the oil prices on the commodity markets (Piot-Lepetit and M'Barek, 2011). The globalization and growing integration of financial and energy markets with agricultural commodity markets, has generated complex interactions among these markets and growing difficulties in understanding the crop price movements to be used in planting decisions.

If we consider the final revenue of the farmers in Northern Italy the water prices are insignificant contributor in the final calculation, so in this model where maximum revenue is optimized we do not explicitly consider the water price, but it is included in the amortization coefficients. Additionally it is considered constant in the future scenarios, since the purpose of this study is aimed to deliver the importance of the CC influencing the water resources management. In Europe the crop market is supported by CAP (Common Agricultural Policy) and Lombardy is one of the most active promoters of this agricultural policy. CAP, as a policy framework implements a system of agricultural subsidies and other programs. However this policy is subject to frequent changes, and therefore the farmers profit is quite difficult to be calculated. Also this policy deems some specific causals like cases where the farmers are allowed to consider contract prices, instead of common market. CAP is not treating all the farmer in same way, it depends of the farm/field size and the aid model adopted for the region, as well as considering awards for the farmers who stick on the European standards for food safety and sustainable environment. The general objectives CAP is represented in figure 2.12. In fact it follows three general pillars that tends to sustainable development and effectiveness. Even though CAP is tending to unify the global prices and reach long term goals in order to improve the Sustainability and satisfy the farmers, the difficulty of defining

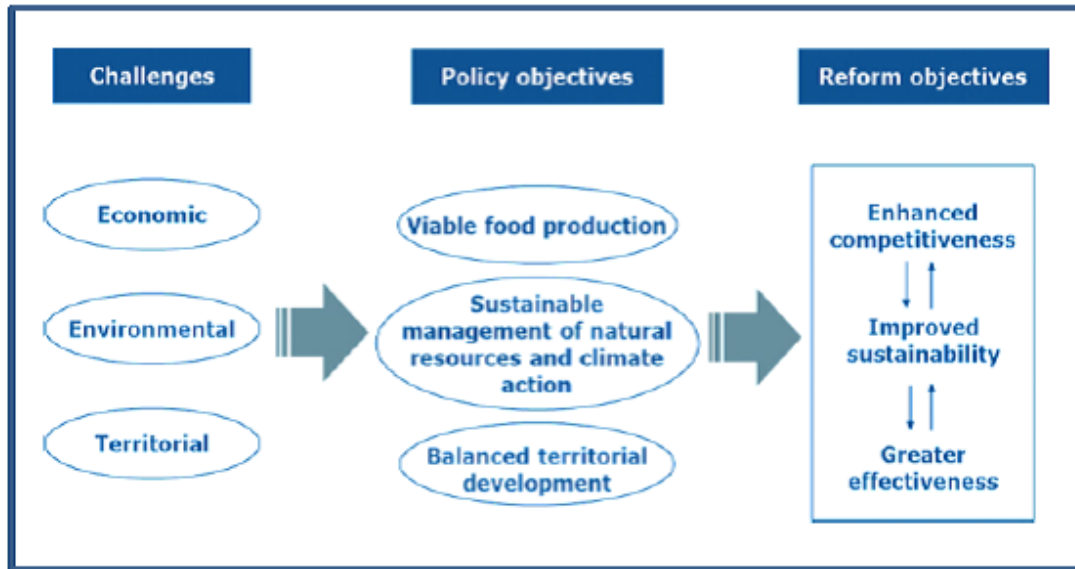


FIGURE 2.12: Common Agricultural Policy

the crop prices through the years does not diminish. The crop market fluctuations are also important since the farmers change the crop land use and maybe considering crop rotation (check Appendix ?). For the baseline scenario the prices of the crops are taken as average producer's price over a certain time period (i.e. 1999 – 2007). The data is corrected from Italian agricultural official websites and verified by experts. In the future scenarios we consider constant prices or the same as the baseline, business as usual. However, the patterns of crop price may change in the future following changed conditions in the crop market, while the water demand may be reduced thanks to improvement in the irrigation technique (e.g. from submersion to more efficient systems) or changes in the crop. Climate change itself will probably drive such changes. Therefore, analysis so far must not be interpreted as a prediction of the future conditions, which would be unrealistic because the socio-economic system will certainly evolve and adapt to reduced water availability, but rather as the demonstration that the current socio-economic conditions cannot be maintained in the future.

2.3.1.3 The impact on the Hydroclimatic regime

In the sectio?? it is explained how does future scenarios are developed and how the uncertainty influence the CC scenarios. The socio-economic factors are one of the main drivers for the uncertainty involvement. This implies that the precipitation and the temperature are strongly influence by the socio economic factors. In order to avoid to

cause confusion the socioeconomic factors are representing the future technology and industry development, or in other words future GHG emissions. To meet projected growth in human population and per-capita food demand, agricultural production will have to significantly increase in the next decades along with the corresponding irrigation consumptions (e.g., Tubiello et al., 2007; de Fraiture and Wichelns, 2010). Yet, water availability, which is often a key factor in determining crop productivity, is expected to decrease over the next century due to climate change impacts (IPCC, 2007), with 3.1 billion urban dwellers expected to experience water shortages by 2050 (McDonald et al., 2011). Squeezing more crop out of the same drop will be one of the biggest challenges of this century (Marris, 2008)[5] in order to guarantee adequate irrigation supply in cropping regions where precipitations are expected to decline. Agriculture is the sector that is most susceptible to short-term and prolonged water shortages. Droughts may result in reduced crop production, soil losses from dust storms, or higher water costs. In general hydrologic fluctuations impose two types of costs on society: the costs of building and managing infrastructure to provide more even and reliable flows and the costs of droughts and floods that occur in spite of the sizable investments that have been made to control flood waters and increase available supplies. Floods and droughts continue to impose significant costs on the Italian Government, and some of these costs have been rising over time. The last conclusion approves our study hypothesis, showing that the fluctuation of the climate variables is strongly related socio-economics aspects and they cannot be considered separately.

2.3.1.4 Flooded area

The consequences of flooding may be developed in a different way. It can be related with the urban flooding or floods in the shore cities, either flooding in the rural area like separated homelands, farms, livestock houses, hungers etc. The flood does not just make material damage but also it influence the economic activities and it blocks the local roads. The latter emphasizes the importance of floods protection. The socio psychological aspect is covering also the people's mindset and acceptance of the floods events, especially considering the touristic seasons. Therefore the socio-economic correspondence towards the floods events has to be urgent and attempt to prevent these hazards. In the policy management of Como Lake the floods are taken into account with calculation of the flooded area. The flooded area is given as a polynomial function

of the lake level in case if it exceeds the threshold, and it defined by experts using GIS and in situ data.

2.3.2 Baseline performance

As it was anticipated in the beginning the baseline performance of the irrigation system and the lake regulation is based on historical data and the experience of the manager and the farmers. Therefore there is no interaction between the farmers among them self's, neither with the water supply agent. The a priori water demand is very basic and assumes max flow in the channel q_{max} during the entire irrigation period(fig2.14.This results with high water wastage as well as money lost for the farmers in case there is not enough water or it is bad managed.

The final land use is dedicated only towards grass and maize planting, as it is a most common cultivating alternative of the farmers. Assigning maize and grass to around 78% and 22% of the cultivated area, respectively. Under this alternative, the water supply objective (i.e., the daily average squared water deficit) is equal to 390 (m^3/s)² and the total economic revenue at the end of the agricultural season is eventually higher than the one that is gained later on, or after 1999. In the light of this policy and the improper lake regulation policy, the farmers went trough lower profit and higher water deficit than before 1999.

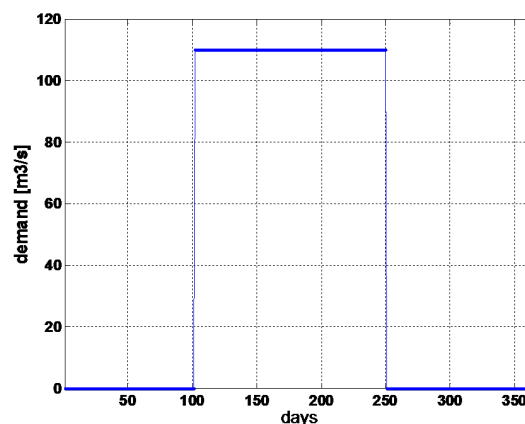


FIGURE 2.13: Water demand before 1999

It is worthy to be mentioned that after 1999 some changes and additional investigation and surveys were done. The procedure resulted with some changes. Therefore it was concluded that the farmers are willing to cultivate grass effectively from march till

December, so the demand was quite modified from the previous one (fig. 2.11). Indeed there were some changes in the land use as well(compare fig 2.14 and fig 2.13). So in the period of 1999-2007 will be our baseline horizon. In this section we are going to present just the baseline performance for a normative demand and fixed land use, trying to do a simulation that is closest to the reality. Therefore in order to estimate the water deficit we use the release optimization with deterministic demand (no farmers feedback,or not adaptive policy), using the weights combinations that are analyzed in some previous studies ,and thus choose the closet to the historical performance.The later mentioned release optimization should be reconstructing scenario of the operator's behavior. Figure2.15 clearly show that in recent years the cultivation of grass is increased and that is why the demand is increased, hence the grass has to be irrigated 9 months.

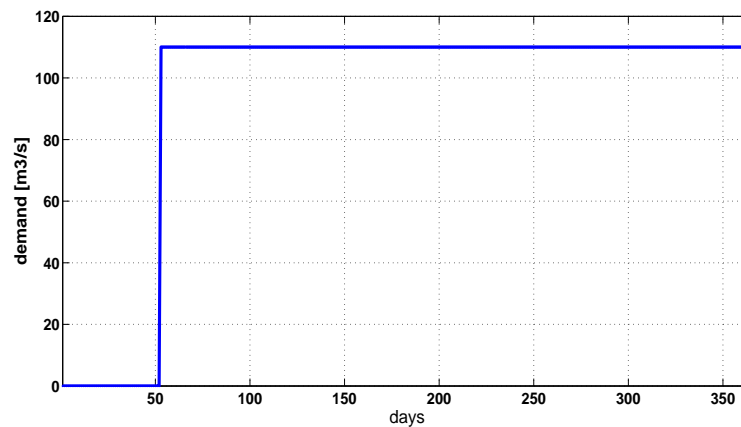


FIGURE 2.14: Irrigation Water demand, before 1999

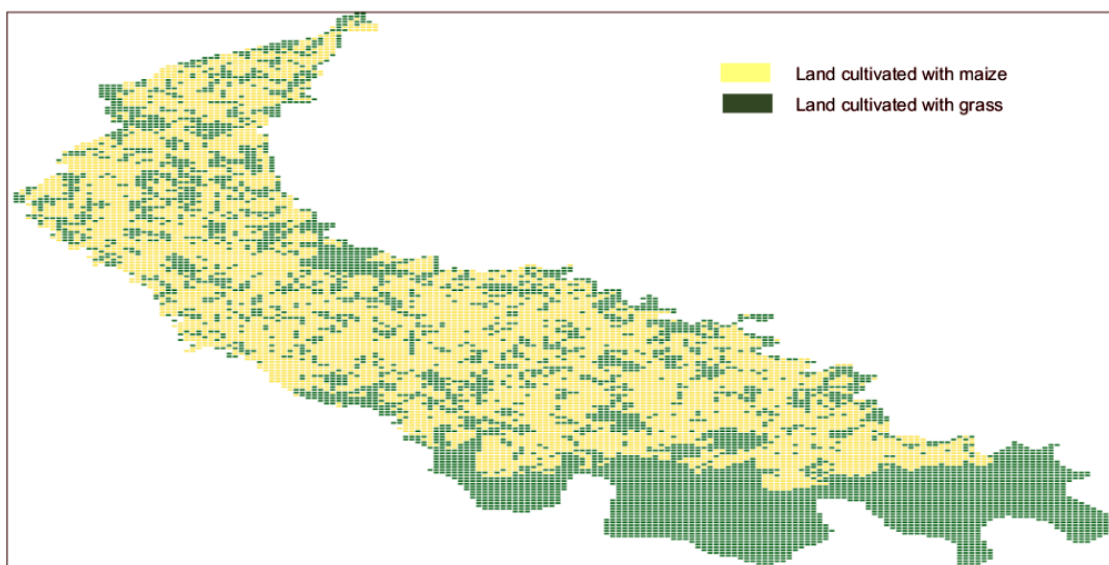


FIGURE 2.15: Baseline Land-use,the green color refers to grass, the yellow to maize

The squared deficit, the profit and the flooded area simulated from the model for the baseline performance are presented in the table below. One can easily figure out that there is big difference between the profit performed before 1999, mentioned above, and the table data. The reason for this discrepancy is that the later is much more comprehensive and includes all the taxes, expenditures and amortization, including the subsidies assigned according the CAP to each farmer (farmers land size is considered). The first is the pure profit analyzed considering the current crop prize without any cost benefit analysis.

It can be noticed that the annual revenue has diminished a bit considering the situation before 1999, but also the water deficit has increased. The change results into switching towards grass cultivation. This is a alert towards policy makers and farmers to consider some adaptive measures. Again, in the baseline alternative, both the water supply and demand practices represent an approximation of the current condition with no guarantee of being the optimal solution for the integrated agricultural water system as there is no interaction between agent's decisions. Later on we are going to explore the lake operator uncertainty analyzing his behavior including the feedback from the farmers for fixed land use.

Chapter 3

METHODS and TOOLS

3.1 Models configuration

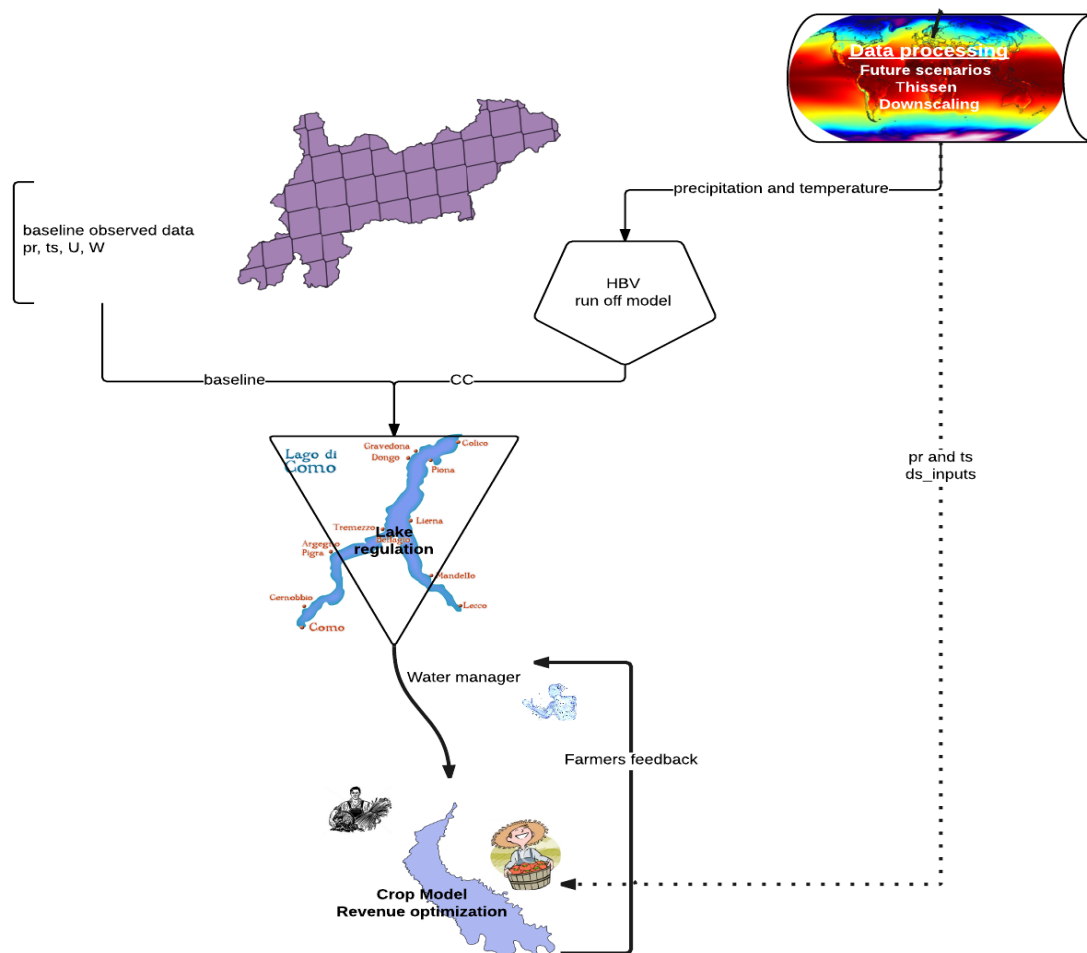


FIGURE 3.1: Model configuration and work-flow

In the introduction was anticipated that we are dealing with a sequence of models whose outputs are used as Inputs one through another, thus in the end to finalize with formation of design indicators as a final output for the optimization problem and definite regulation policy. Therefore we have 3 major models that are producing different outputs, used for specific purposes. In the following diagram the intercommunication and the flow of the modeling procedure among the models is presented.

The descriptive 3.1 causal network presented above clearly point out the connections among the models and the management policy. Therefore first we deal with future data processing, or downloading, locating and downscaling certain GCM/RCM scenarios. Than after the downscaling and adapting the data, we proceed the data towards the HBV runoff, model which performs hydro climatic modeling of the data and produce the discharges in the Lake. Now having the inflow in the lake we can settle the mass balance equation for the lake model. Than the regulation policy is being made, and according the release strategy is being decided. The farmer's receive the water, the complex district model is running estimating the possible yield and maximize the farmer's revenue. In order to maximize the revenue the model produce the optimal water demand, which is feedback from the farmers for the next management policy.

3.1.1 HBV (*Hydrologiska Byråns Vattenbalansavdelning*)

HBV stands for Hydrologiska Byråns Vattenbalansavdelning (Bergstrom, 1976; Bergstrom et al., 1995) and it is a lumped rainfall-runoff model developed for operational flood forecasting in Sweden. Runoff models mathematically are describing the relation between rainfalls and runoffs of the catchment area or watershed. Simply, they are producing runoff hydrographs using as input the precipitation hydrograph, or they do the conversion. The HBV model is a conceptual model that simulates daily discharge using daily rainfall and temperature, and monthly estimates of potential evaporation as input (Seibert, J., 1999. Conceptual runoff models - fiction or representation of reality?) [6]. The model consists of different routines, where snow-melt is computed by a degree-day method, groundwater recharge and actual evaporation are functions of actual water storage in a soil box, runoff formation is represented by three linear reservoir equations and channel routing is simulated by a triangular weighting function (Fig below 3.2).

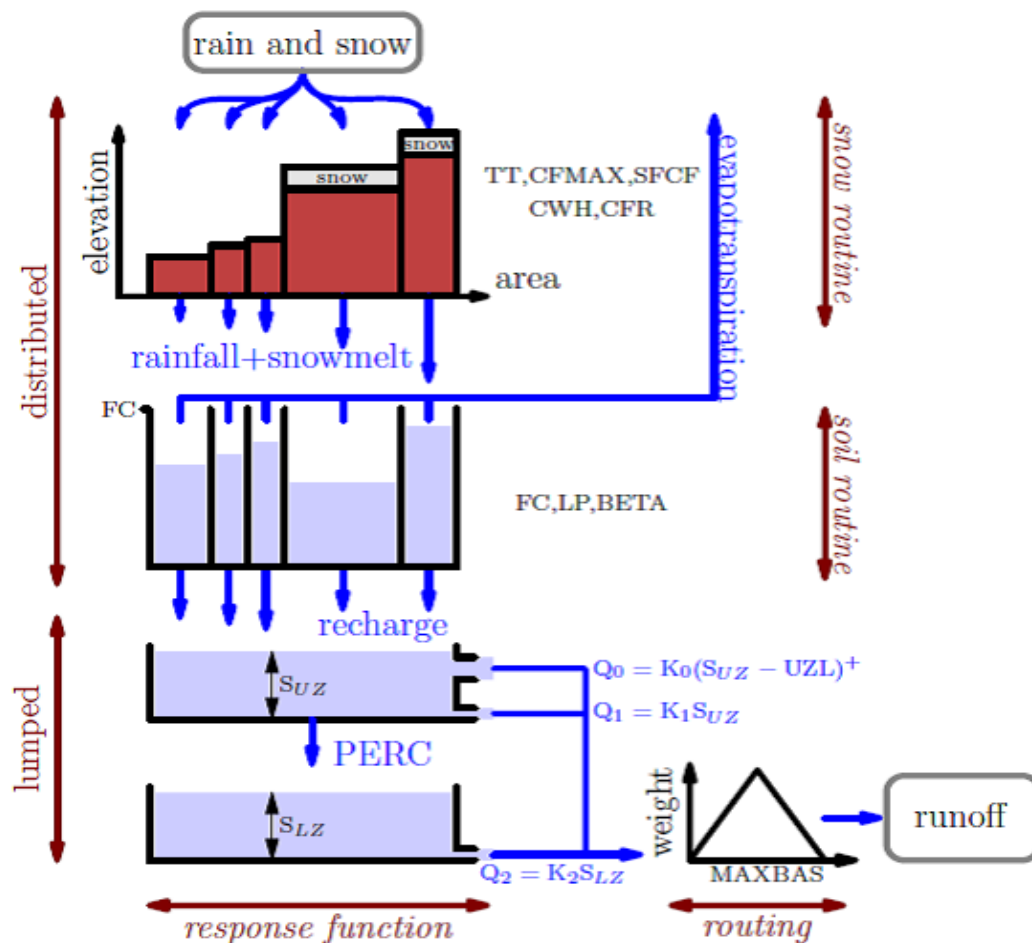


FIGURE 3.2: HBV working scheme

This model is widely used and found interpretation in 30 different institutes. So this models has to be calibrated according our study site characteristics. The calibration on the HBV model aims to estimate the best values for the 12 parameters with respect to one (or more) suitable model performance metrics (e.g., mean square error, coefficient of determination, etc). However, the HBV calibration can be a difficult operation due to the complexity and non-linearity of the modeled processes. Anyway the calibration had been already performed, so we only concentrated on the processing the model inputs and produce reasonable discharges. Thus the input of stream flow discharges is 0, since we have the parameters already calibrated. The data for the calibration as well as for downscaling are mostly taken from the Cancano station located in the Como catchment area. Moreover the role of the hydrological model in this study is to reproduce the discharges or inflows in Lake Como, out of the downloaded CC EUROCORDEX data, which is only the average surface temperature and the areal precipitation(estimated

using the Thissen weighting method). Therefore all the rest of the parameters are assumed that remain same as the HBV was once calibrated for Como Lake catchment. The simulation of the HBV model[7] aims to estimate the river basin discharges, given a time series of model inputs (i.e., temperature and precipitation) and the values of the model parameters(that are defined and stored with the calibration process). The implementation of the code assumes running 5 different functions:

1. The snowmelt: estimate the effective precipitation for the current day t . This function is taking into account the average temperature and decides if the precipitation is solid(snow) or liquid. Thus the snow melt contributes to the effective precipitation, and in same time it is removed from the snow storage.
2. The soil function: It estimates the soil storage of the shallow layer for the current day t . If the soil moisture storage is greater than the maximum capacity, the runoff Q_{runoff} is equal to the effective precipitation plus the excess of soil moisture storage with respect to the maximum capacity. The soil moisture storage is therefore equal to its maximum capacity. Conversely, if soil storage \leq maximum capacity, a portion of the effective precipitation (which depends on the parameter) goes into the soil storage and only the remaining part contributes to Q_{runoff} . Then, the function estimates the actual evapotranspiration and compares it with the soil moisture storage. The potential evapotranspiration is computed according to the Hamon method (Hamon, 1961) and depends on the average temperature T_{avg} and the location (i.e., latitude) of the catchment according to the following formulation.
3. The discharge function: aim of this function is to compute the discharge Q_{all} , which depend on the near surface flow Q_0 (if higher than the capacity), the inter flow Q_1 (if still remaining water after Q_0 flows out), and the base flow Q_2 (estimated if there is water left that percolates after previous two flows discharge out of the basin at moment t).
4. The routing function: The aim of this function is to transform the discharge Q_{all} using the parameter $MaxBas$ for routing.
5. The backflow function: This function reinitialize to zero the arrays used for the routing depending on the parameter $MaxBas$ ¹.

¹a parameter that is defining the triangular weighting function, seen in fig.3.2

This output is used in the lake regulation and optimization problem as integrated input of the SDP, or Bellman function “H” using backward forward optimality.

HBV model disadvantages This hydrological model show some disadvantages from the simulation results. In some studies (Anghileri, Pianosi, Soncini-Sessa, 2011, Driessen2010) [3], a simulation of the model is done using historical data in order to compare the results. Naturally the results were not matching with the historical inflows, but they were satisfying for robust interpretations of the inflows. In this experiment we noticed that the model does not produce the real inflows in the lake. In fact the model is very sensitive to a dry spells (explained in section, Ch.4) and if the soil storage is empty, then it produces zero inflows. This is slightly impossible in reality, hence it means that all the river bed are dried out. This means that the model does not include the groundwater storage and the movement of the ground water as well. Also it does not consider the current state of the rivers and the lake. And finally it is not taken into account the glaciers dynamics. Therefore the model is giving us inflows with quite big safety factor, since the later mentioned factors might influence the inflow significantly. Also the inflows associated with 0 m³/s might influence the lake regulation model and the stochastic representation of the inflows in the optimization procedure. This issue should be considered carefully before running the future scenarios. Nevertheless, the model developers did try to implement at least the groundwater, introducing some parameters and initial conditions, but the dynamics of the GW and the current flow of the existing water bodies is still an abstract issue for the hydrological modeling in general(Seibert, J., 1999. Conceptual runoff models - fiction or representation of reality?)[6].

3.1.2 Lake regulation model

In order to start the discussion about the methodology that is used in order to model the lake and obtain the regulation policy, we will recall the IPWRM framework and explain the phase of Design Problem(Roncini Sessa, ACC)[8]. In that sense we are going to explain the procedure starting from the management policy. At first we should start with explaining the components of the lake regulation model.

Anyhow the lake dynamics is quite intuitive and assumes the mass balance equation that includes the following elements:

- storage s_{t+1} .
- inflow a_{t+1} , usually given in m³/s.
- release r_{t+1} is the release.
- $e_t + 1$ is an evaporated volume per unit of surface area.

Consequently the reservoir is modeled in traditional way balancing the inflows and outflows:

$$s_{t+1} = s_t + a_{t+1} - r_{t+1} - S(s_t) \cdot e_{t+1} \quad (3.1)$$

The inflow is formulated as eq.3.2, where the disturbance is described by a log normal probability function, which is computed using the historical inflow time series, or the inflow CC data produced by the HBV model.

$$a_{t+1} = f_t^a(\varepsilon_{t+1}^a)\varepsilon_{t+1}^a \sim \phi_{t+1}^a \quad (3.2)$$

Now we have to define also the release function r_{t+1} is modeled using the released function r_{t+1} , which is accounted as the most complicated one. The minimum and maximum release functions are shown in the figure below. And the release in real life vary somewhere in this space, depending of the storage and inflow.

$$r_{t+1} = R_t(s_t, u_t, a_{t+1}, e_{t+1}) = \begin{cases} \nu(s_t, a_{t+1}, e_{t+1}) & \text{if } u_t \leq \nu(s_t, a_{t+1}, e_{t+1}) \\ V(s_t, a_{t+1}, e_{t+1}) & \text{if } u_t \geq V(s_t, a_{t+1}, e_{t+1}) \\ u_t & \text{otherwise} \end{cases} \quad (3.3)$$

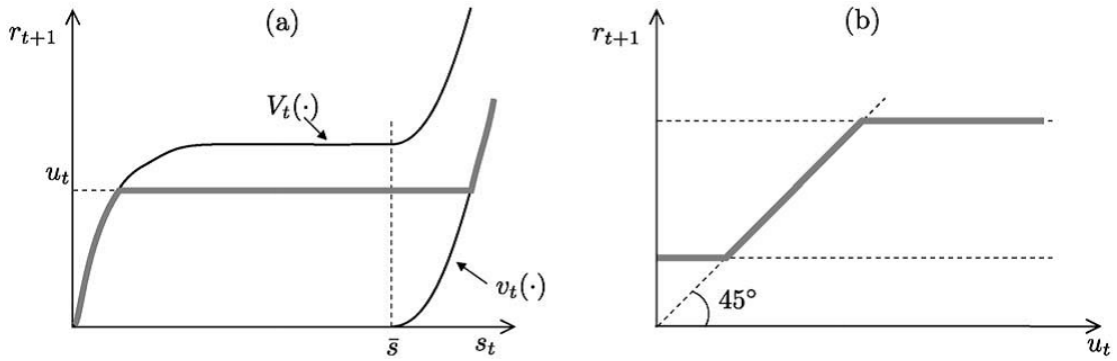


FIGURE 3.3: The minimum and maximum release functions $v_t(\cdot)$ and $V_t(\cdot)$ and two sections (heavy line) of the release function $R_t(\cdot)$: (a) with respect to the storage s_t , given a_{t+1} , e_{t+1} and u_t ; (b) with respect to the release decision u_t , given s_t , a_{t+1} and e_{t+1} .

The functions above give the normative constraints and the regulation range, also called limits of active storage. If we use the denotation normative the symbols might be written using \mathbb{N} instead of \mathbb{R} , but the meaning is the same. The only state variable in this model is s_t , and the rest of the variables (internal or input/output variables) are explained above including the w_t which is the deterministic water demand.

3.1.3 The management problem

In the beginning of this chapter it was anticipated that we are going to deal with two problems, pure planning and pure management problem. In reference two models are considered, the crop model dealing with the planning action assuming deterministic scenario for water demand and the lake regulation, which covers the Control problem, or planning management. The procedure is interconnected performing an off line closed loop strategy, which will be explain at the end of this chapter. In the beginning it would be useful that we will refer to the management policy as a release policy or a control law, since we are dealing with pure management problem and a reservoir. Most commonly used control law is is point valued (PV) for which given information ζ_t at time t provides decision u_t . $u_t = m(\Delta)$.

Nevertheless the regulator might find this law as a limited since it is the unique information supplied to him. Therefore it is preferable to use a set valued policy (SV), where $u_t = M(\cdot)$, where $M_t(\cdot)$ is a subset of policies referring to u_t . Alternatively the SV policy might be defined as a set of PV controls, $M_t(\Delta) = m_t(\Delta)$.

Another useful terminology is to define the two types of polices: on line and off line, according the time when they are designed, at the very moment or a priori. The first one requires the problem to be solved at every time t , simultaneously, which means that observed state \mathbf{x}_t is required and the information \mathbf{w}_t is acquired. The later one produce the policy at time $t+1$ knowing the state at time t . Knowing this it means that it is a long term policy that move the system into the state \mathbf{x}_{t+1} . In that sense the second one give us policy on demand. In addition there are few differences that might refer to these polices. The first difference between off-line and on-line policies is that the first cannot exploit exogenous information (i.e. the knowledge of deterministic disturbances), while the second can. The second difference is that in order to define an off-line policy, it is necessary to compute the control \mathbf{u}_t a priori for all the possible occurrences of the state \mathbf{x}_t , while with an on-line policy, the control will be calculated only as a particular state occurs.

The elements of the Design problem are similar to the planning problem. Therefore we will have defined the design indicators, the horizon, the step cost, the objectives and the design scenario. In our case we will deal with PV polices so the case of SV policy will not be explained, since it includes the regulator decision, which is beyond of the study. Here again we deal with randomness of the indicators and we have to perform filtering. Under assumption of a finite horizon the La Place criterion for a pure management policy is defined as (Soncini-Sessa et al., 2007a):

$$\mathbf{J}^* = \min_p E_{\{\varepsilon_t\}_{t=1,\dots,h}} [\mathbf{J}(\mathbf{x}_0^h, \mathbf{u}_0^{h-1}, \mathbf{w}_0^{h-1}, \varepsilon_1^h)] \quad (3.4a)$$

subject to

$$\mathbf{x}_{t+1} = f_t(\mathbf{x}_t, \mathbf{u}_t, \mathbf{w}_t, \varepsilon_{t+1}) \quad t=0,1,\dots,h-1 \quad (3.4b)$$

$$m_t(\mathbf{x}_t) = \mathbf{u}_t \in \mathcal{U}_t(\mathbf{x}_t) \quad t=0,1,\dots,h-1 \quad (3.4c)$$

$$\varepsilon_{t+1} \sim \phi_t(\cdot) \quad t=0,1,\dots,h-1 \quad (3.4d)$$

$$\mathbf{w}_0^{h-1} \text{ given scenario} \quad (3.4e)$$

$$\mathbf{x}_0 \text{ given} \quad (3.4f)$$

$$p \triangleq \{m_t(\cdot); t = 0, 1, \dots, h-1\} \quad (3.4g)$$

$$\text{any other constraints } t=0,1,\dots,h-1 \quad (3.4h)$$

where $\mathbf{J} = [J_1, J_2, \dots, J_n]$ is a vector of n different management objectives (or design criteria), \mathbf{x}_t is the vector of the state variables of the system (whose transition is given by equation (3.12b)), \mathbf{u}_t is a vector of control variables (management decisions) which are defined by the control law $m_t(\mathbf{x}_t)$ and can assume values only among the feasible set \mathcal{U}_t , \mathbf{w}_t is a vector of the design scenario which is constituted by the trajectory of all the variables that are not influenced by the alternatives being examined, and so does not depend upon the choice of the Decision Maker, ε_{t+1} is a vector of stochastic disturbances and p is the point-value control policy. Additionally, we might deal with infinite horizon. Therefore the same alternatives holds for solving it, TDC or AEV, and the receding horizon which is characterized in the on line polices. In this work we are not going to explain these principals since they are not used in the modeling concept of this case study.

3.1.4 Regulation policy

The above explained management problem will be applied to the lake regulation policy. We consider a coupled model that intercommunicate in a loop, so in our release policy we will not have nested planning actions up, but only the Control Law. That is the core of this study, however in the end we are going to present, the co adaptation problem, only for the baseline scenario, assuming the re optimization of the current situation.

The final goal of this problem is to determine the optimal regulation policy p which, at each time instant $t = 1, \dots, h$ ($h = 365$) and given the current state \mathbf{x}_t of the system, suggests the control $\mathbf{u}_t \in m(\mathbf{x}_t)$ to be adopted. The policy optimization will be carried out accounting for two objectives: minimization of floods on the reservoir shores (J^{flood}) and minimization of water deficits in the downstream irrigation district (J^{irr}).

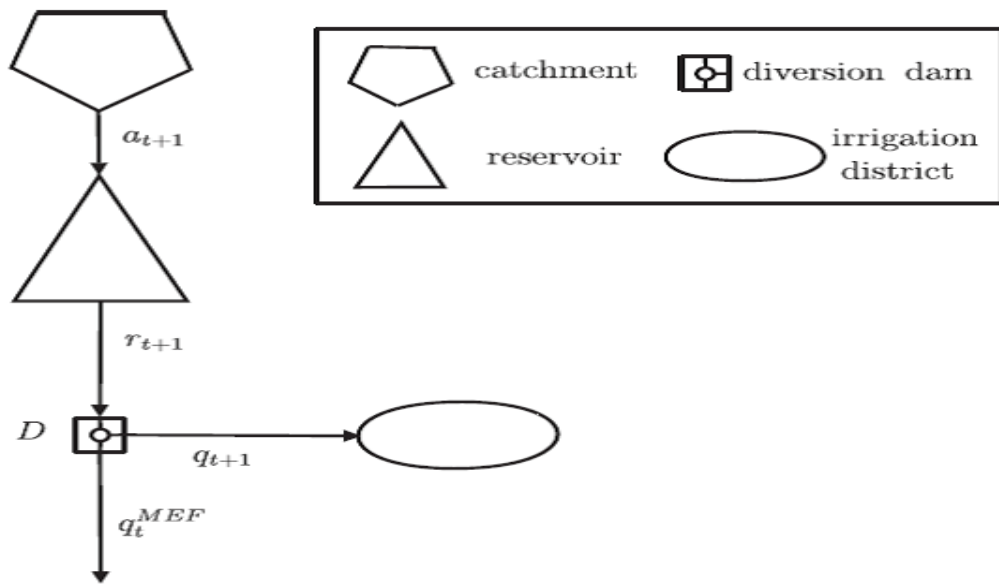


FIGURE 3.4: Schematization of the simple system considered to formulate the different design problems.

The indicators are defined as:

- J^{irr} , defined as a water deficit in the irrigation, where g_t is the step cost related with the irrigation supply. Since we deal with a finite horizon $h=365$ days, the indicators are also called step indicators or step costs, as mentioned above. The Laplace criterion is used in this case.

$$J^i = E_{\{\varepsilon_t^a\}_{t=1,\dots,h}} \left[\sum_{t=0}^{h-1} g_t^i(q_{t+1}, W_t) \right] \quad (3.5)$$

- Similarly defined is the second one J^{flood} , related with the flooding indicator. The flow q_{t+1} is modeled due to the diversion dams, or the flow in river Adda, also considering the minimum environmental flow.

$$J^f = E_{\{\varepsilon_t^a\}_{t=1,\dots,h}} \left[\sum_{t=0}^{h-1} g_t^f(s_t) \right] \quad (3.6)$$

The flow q^{irr} is modeled according to the diversion dams and the flow in river Adda, also considering the minimum environmental flow.

$$q_{t+1} = \{(r_{t+1} - q_t^{MEF}), \min\{\widehat{W}_t, q_t^{msx}\}\} \quad (3.7)$$

Where the W_t is the water demand estimated in the Crop model, after the first loop, and q_{max} is the maximum flow in Muzza channel. It is worthy to mention that a good performance of the Crop model is more than welcome, since every overestimation of W_t is a loss, while every lower is a deficit (Galelli Soncini-Sessa, 2010)[1]. With reference to the water system in Figure 3.4, the formalization of the optimal control is following:

$$J^* = \min_p J \quad (3.8a)$$

subject to

$$\varepsilon_{t+1}^a \sim \phi_t^a(\cdot) \quad (3.8b)$$

$$a_{t+1} = f_t^a(\varepsilon_{t+1}^a) \quad (3.8c)$$

$$s_{t+1} = f_t^s(s_t, u_t, a_{t+1}) \quad (3.8d)$$

$$r_{t+1} = R_t(s_t, u_t, a_{t+1}) \quad (3.8e)$$

$$u_t = m_t(\mathbf{x}_t) \in \mathcal{U}_t(s_t) \quad (3.8f)$$

$$p \triangleq \{m_t(\cdot); t = 0, 1, \dots, h-1\} \quad (3.8g)$$

$$q_{t+1} = \min[(r_{t+1} - q_t^{MEF})^+, \min(W_t, q_t^{max})] \quad (3.8h)$$

$$W_t \text{ given scenario} \quad (3.8i)$$

$$x_t = s_t \quad (3.8j)$$

$$\mathbf{x}_0 \text{ given} \quad (3.8k)$$

where in equation 3.8a the design objective J is defined as follows:

$$J = \lambda \cdot J^{floods} + (1 - \lambda) \cdot J^{irr} \quad (3.9)$$

where the *weighting method* through the coefficient λ is applied to transform a Multi Objectives Problem in a Single Objective one² and, by applying the Laplace filtering criterion and considering a finite horizon h , as it is shown for the two objectives can be defined in the eq.3.5 and 3.9. Here weighted method is adopted and the problem is

²The same method allows, by letting λ vary gradually from 0 to 1, to determine the Pareto frontier of the problem, even though some Pareto optimal solutions cannot be found in the case of a convex Pareto frontier. In this case, the contextual application of the *constraint method* allows to find the solutions that the weighting method could not find (Soncini *et al.*, 2007a).[8]

derived to single objective function. If the parameters vary there is formation of the Pareto frontier. The solution of this problem has to be solved in the phase of estimating effects and then evaluated using some of the evaluation or decision making methods, like MAUT if we deal with stochasticity. However this problem is solved easily since the Pareto frontier or set of supported points can be easily is composed of the union of the convex parts of the Frontier, each of which can be defined as a part of the Frontier such that each segment, whose extreme points belong to it, is constituted by feasible policies, i.e. by policies such that the constraints of problem are satisfied. The Set of Supported Points coincides.

Step Costs The step indicators sometimes very often are not associated with a single component, aggregation of one or more components is required. Thus the objective functions or the performance indicators have their step costs. The flood reduction objective is defined by the following step cost:

$$g_t^{flood} = \begin{cases} 0 & \text{if } h_t < 1.24 \\ h_t^4 + b \cdot h_t^3 + ch_t^2 + d \cdot h_t + e & \text{if } h_t \geq .24 \end{cases} \quad (3.10)$$

,which expresses the daily flooded area (m^2) in the city of Como, the city most subjected to flood events in the whole upstream area, as a function of the lake level h_t . The parameters a,...,e were estimated on a set of historical measures of lake levels and corresponding flooded areas over the horizon 1980–2004.

The downstream water supply objective can be expressed as a function of the estimated total water demand at the lake outlet. Through interviews with hydropower companies(considering the above-mentioned gentleman agreement) and farmers, a significant risk aversion(better many days of low deficit,instead one long and big water deficit) emerged and the following step cost was identified:

$$g_t^i = [(\widehat{W}_t - q_{t+1})^+]^2 \quad (3.11)$$

3.1.5 District mode

In the chapter 2 we have seen that we are going to deal with an agricultural district that is composed of 66 different farmers. One approach suggested by the literature

for describing the behavior of the farmers and water resources is Multi agent based modeling. In fact here we have an attempt to perform that state of art. Therefore, one possible method proposed by Modi et al.[9], 2005 is to use distributed agent system and model the farmers as different agents (for further information see AppendixC) The methodology suggested above and described in AppendixC Point us of usage of the DCOP as a method in order to formulate the planning problem, integrated with the crop model . Since the application of these principles affects "common goods" like water bodies and soil, the responsibility for pollution is difficult to point out. Thus, farmers should cooperate to find an agreement on the amount of fertilizers and pesticides that each of them is allowed to use, so that the environmental quality standards imposed by the new regulations would be achieved. In this work, farmers are modeled in a distributed way by means of the FDP model and considered as selfish and rational agents in a Multi-Agent System; the boundaries of the system are assumed to coincide with the agricultural district; finally, the environmental quality standard scan be instead considered as global district-level constraints when global environmental objectives for Distributed Constraint Optimization Problem (DCOP, see Modi et al., 2005)[9, 10] methods. A Constraint Satisfaction Problem (CSP) is to find a consistent assignment of values to variables under given constraints. The final target of this section, referring to this model will be the application of Artificial Intelligence algorithms to find the optimal allocation of farmers' variables that allows to maximize the individual objective and, at the same time, comply with regulated global environmental quality standards at the district-level. Performing the planning procedure considering MAS, we need design indicators to develop the objective functions related with each farmer. As it is well known the indicators are just outputs from a model. In that sense in the section below we offer a framework of the distributed crop model. The model designed in this work is a distributed-parameter, conceptual model which accounts for the space variability of soils and crops, as well as of meteorological and irrigation inputs, by subdividing the irrigation district with a regular mesh that creates squared cells sized 250x250 m²: soil and crop characteristics as well as meteorological inputs and irrigation supply are homogeneous in each cell of the mesh, but may vary from cell to cell. The core of the distributed-parameter model is the Crop Growth Model, which is applied to each cell i of the space domain to simulate and estimate the growth development of each crop considered ($up \in Up$, exhaustive procedure) during the whole time horizon (a year). The output of this model is a vector of the expected crop yields corresponding to each

possible crop typology, which, along with the crop sale price (deterministic scenario), allows farmers to choose the most profitable crop for each cell they own.

Planning problem In the Introduction it is noted that the main purpose and the core of this study is exploring of the deterministic simulation of the models, which assumes no planning action. however in section 4.4, we offer a co adaptive simulation, which assume a crop rotation, for better balanced water demand feedback and for higher revenue. Therefore we presume a planning action which is nested in the management problem of the farmers objective (maximizing the revenue). This crop rotation defines the simplest planning problem assuming no stochastic distribution for u_p , since there are only 5 offered possibility to choose, and the choice depends of their characteristics and the water availability. For this reasons we offer a brief explanation of the integrated management and planning Design Problem assuming La Place filtering criterion and a finite horizon, as it was mentioned before.

$$\mathbf{J}^* = \min_{u^p, p\{\varepsilon_t\}_{t=1, \dots, h}} E[\mathbf{J}(\mathbf{x}_0^h, \mathbf{u}^p, \mathbf{u}_0^{h-1}, \mathbf{w}_0^{h-1}, \varepsilon_1^h)] \quad (3.12a)$$

subject to

$$\mathbf{x}_{t+1} = f_t(\mathbf{x}_t, \mathbf{u}_t, \mathbf{w}_t, \varepsilon_{t+1}) \quad t=0, 1, \dots, h-1 \quad (3.12b)$$

$$\mathbf{u}^p \in \mathcal{U}^p \quad (3.12c)$$

$$m_t(\mathbf{x}_t) = \mathbf{u}_t \in U_t(\mathbf{x}_t, \mathbf{u}^p) \quad t=0, 1, \dots, h-1 \quad (3.12d)$$

$$\varepsilon_{t+1} \sim \phi_t(\cdot) \quad t=0, 1, \dots, h-1 \quad (3.12e)$$

$$\mathbf{w}_0^{h-1} \text{ given scenario} \quad (3.12f)$$

$$\mathbf{x}_0 \text{ given} \quad (3.12g)$$

$$p \triangleq \{m_t(\cdot); t = 0, 1, \dots, h-1\} \quad (3.12h)$$

$$\text{any other constraints } t=0, 1, \dots, h-1 \quad (3.12i)$$

Crop growth model The model designed in this work is a distributed-parameter, conceptual model which accounts for the space variability of soils and crops, as well as of meteorological and irrigation inputs, by subdividing the irrigation district with a

regular mesh that creates squared cells sized $250 \times 250 \text{ m}^2$: soil and crop characteristics as well as meteorological inputs and irrigation supply are homogeneous in each cell of the mesh but may vary from cell to cell. The core of the distributed-parameter model is the Crop Growth Model, which is applied to each cell i of the space domain to simulate and estimate the growth development of each crop considered³ ($\forall \mathbf{u}^p \in \mathcal{U}^p$, exhaustive procedure) during the whole time horizon (a year). The output of this model is a vector of the expected crop yields corresponding to each possible crop typology, which, along with the crop sale price (deterministic scenario), allows farmers to choose the most profitable crop for each cell they own.

Yield response to water

The fundamental equation of the Crop Growth Model is an empirical function commonly known as "Yield response to water" which was developed, calibrated and extensively tested in the FAO Irrigation and Drainage Paper 33 (Doorenbos *et al.*, 1979)[11]. It is a linear crop-water production function that describes the relationship between actual crop yield and possible water stresses happening during the crop growing period as a result of insufficient water supply from rainfall or irrigation. Thus, it basically allows to compute the actual crop yield at the end of the growing season on the basis of a record of the daily water deficits (if any).

$$1 - \frac{Y_{real}^i}{Y_{max}^i} = k_y \left(1 - \frac{ET_{real,tot}^i}{ET_{0,tot}^i}\right) \quad (3.13)$$

where Y_{max}^i and Y_{real}^i [$\frac{kg_{market}}{cell}$] are the maximum and actual yields of the crop planted on cell i , $(1 - \frac{Y_{real}^i}{Y_{max}^i})$ [-] the yield decline caused by the water stress $(1 - \frac{ET_{real,tot}^i}{ET_{0,tot}^i})$ [-], $ET_{0,tot}^i$ and $ET_{real,tot}^i$ [mm] the maximum and actual evapotranspiration during the whole growth period, the relative water stress, and k_y the crop-dependent proportionality factor between relative yield decline and relative reduction in evapotranspiration. As Figure 3.5 shows, crops that are more sensitive to water stresses have higher k_y values (generally slightly higher than 1), whereas more resistant ones have lower k_y values.

By rearranging equation (??) to the following form

³The following equations contain a series of parameters that depend on the crop typology that is being modeled. Notational accuracy would require to express this dependence using a subscript (e.g. x_{crop}), but in order to lighten the notation itself, the subscript will be removed. However, the dependence will be highlighted contextually and it is possible to refer to section ?? for the complete list of crop-dependent parameters.

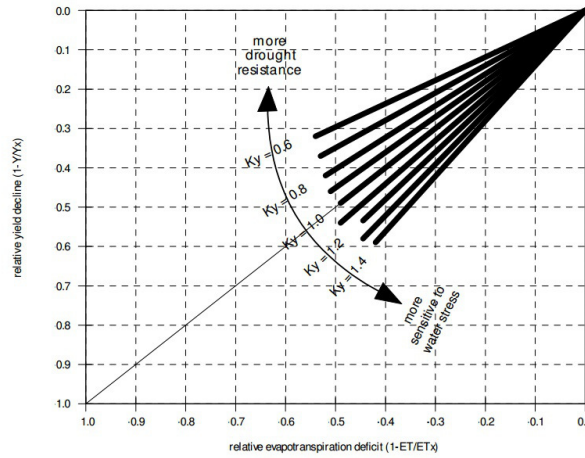


FIGURE 3.5: Relationship between crops' sensitiveness to water stress and relative yield response factor Ky .

$$Y_{real}^i = Y_{max}^i \left[1 - k_y \left(1 - \frac{ET_{real,tot}^i}{ET_{0,tot}^i} \right) \right] \quad (3.14)$$

it is possible to see that the actual crop yield in cell i Y_{real}^i (on the basis of which farmers' objective function is computed) depends on three terms: maximum achievable yield Y_{max}^i when no water stresses ever happen during the growing season; sum of the daily reference evapotranspiration $ET_{0,tot}^i$ and sum of the daily actual evapotranspiration $ET_{real,tot}^i$ during the whole growth period, defined as follows

$$ET_{0,tot}^i = \sum_{t=1}^h ET_{0,t}^i \quad (3.15)$$

$$ET_{real,tot}^i = \sum_{t=1}^h ET_{real,t}^i \quad (3.16)$$

The maximum yield Y_{max}^i will be computed by means of the following equation:

$$Y_{max}^i = HI_{opt} \cdot B_{max}^i \quad (3.17)$$

where $HI_{opt} \in [0, 1]$ is the crop's optimal Harvest Index, an adimensional crop-dependent coefficient representing the marketable fraction of B_{max}^i $\left[\frac{kgDryMassAboveGround}{cell} \right]$, that is the maximum biomass produced at the end of an optimal growing season, namely when no

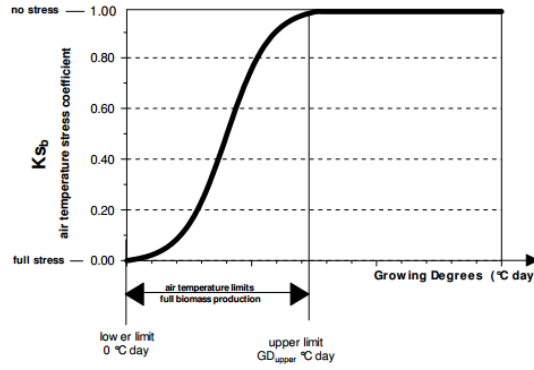


FIGURE 3.6: Air temperature stress coefficient for reduction of biomass production when average temperature is lower than the optimal one GD_{upper} .

nutrients stresses take place⁴.

B_{max}^i can be computed as follows:

$$B_{max}^i = \sum_{t=1}^{365} WP \cdot \frac{Tr_t^i}{ET_{0,t}^i} \cdot Ks_{b,t}^i \quad (3.18)$$

where WP represents the crop's Water Productivity [$\frac{kgDryMassAboveGround}{day \cdot cell}$], Tr_t^i and $ET_{0,t}^i$ [mm] represent the transpiration and reference evapotranspiration at time t , $Ks_{b,t}^i \in [0, 1]$ is an adimensional stress coefficient and is defined through a logistic curve defined in the interval $[0, GD_{upper}]$, where GD_{upper} [$^{\circ}C$] is the crop-dependent minimum temperature that avoids biomass production reductions due to cold conditions (Raes *et al.*, 2010).

The Water Productivity WP can be computed as follows:

$$WP = WP_{std} \cdot fCO_2 \cdot S^i \quad (3.19a)$$

$$fCO_2 = \frac{\frac{concCO_{2,year}}{concCO_{2,ref}}}{1 + 0.000138 \cdot (concCO_{2,year} - concCO_{2,ref})} \quad (3.19b)$$

$$concCO_{2,year} = concCO_{2,ref} + 2 \frac{ppm}{year} \cdot (year - 2000) \quad (3.19c)$$

⁴Notice that equation 3.18 accounts for both water and temperature stresses by means of the terms Tr_t^i and $Ks_{b,t}^i$.

where S^i [m^2] is the surface of the cell ($62500 m^2$ in this model, being the cells shaped as squares with a 250 m side length), WP_{std} [$\frac{kgDryMassAboveGround}{day \cdot m^2}$] the crop's water productivity value per unit surface standardized for the $conc_{CO_2,ref} = 369.41 ppm$ measured in the reference year 2000.

Equation 3.19b updates the standardized values to the current average CO_2 concentration ($conc_{CO_2,year}$), which can be estimated through equation 3.19c (Raes *et al.*, 2010).

Water balance module In order to apply the previous equations three last variables for the whole growing season still need to be determined: $ET_{0,t}^i$, Tr_t^i and $ET_{real,t}^i$. These are clearly related to the hydrological balance of each cell in the considered space domain. The water balance module of the Crop Growth Model allows to accomplish two basic goals:

1. the computation of the hydrologic balance in the root zone
2. and the simulation of the irrigation water distribution

In each cell of the space domain on a daily basis. It seems noteworthy to highlight that the latter functionality of the model (Galelli *et al.*, 2010) allows to determine the dynamics of the irrigation management, and thus the integration with the Regulation Policy optimization to build the Coupled Model.

In the water balance module (Facchi *et al.*, 2004) each individual cell identifies a soil volume which extends from the soil surface to the lower limit of the crop root zone, and in accordance with this schematization a one-dimensional representation of the hydrological processes is adopted within it. In addition, the soil volume of each cell is subdivided into two layers: the upper one (*evaporative layer*) represents the upper 15 cm of the soil; the bottom one (*transpirative layer*) represents the root zone and has a time-varying crop stage-dependent depth $Z_{r,t}^i$. The two layers are modeled as two non-linear reservoirs in cascade (see Figure 3.7). The water percolating out of the bottom layer constitutes the recharge to the groundwater system.

The dynamics of the water content $U_{1,t}^i$ [mm] in the evaporative layer is governed by the following balance equation:

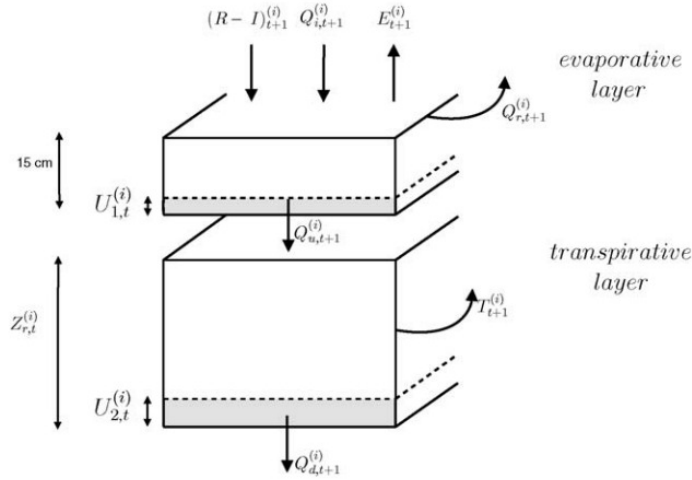


FIGURE 3.7: Schematic representation of the soil layered structure considered in the distributed model and the corresponding terms involved in the water balance.

$$U_{1,t+1}^i = U_{1,t}^i + R_{t+1}^i + I_{t+1}^i + Q_{r,t+1}^i + E_{t+1}^i - Q_{u,t+1}^i + Q_{i,t+1}^i \quad (3.20)$$

where all the variables are expressed in [mm] and refer to cell i and time interval $[t, t+1)$. R_{t+1}^i is the rainfall, I_{t+1}^i is the canopy interception, $Q_{r,t+1}^i$ is the net runoff from the cell, E_{t+1}^i is the evaporation, $Q_{u,t+1}^i$ is the water percolating to the transpirative layer and $Q_{i,t+1}^i$ is the irrigation supply **which, all in all, depends on the regulation policy of the upstream reservoir**.

A similar equation describes the dynamics of the water balance in the transpirative layer:

$$U_{2,t+1}^i = U_{2,t}^i + Q_{u,t+1}^i - Tr_{t+1}^i - Q_{d,t+1}^i \quad (3.21)$$

where all the variables are again expressed in [mm] and refer to the time interval $[t, t+1)$. Tr_{t+1}^i represents the transpiration and $Q_{d,t+1}^i$ is the outflow from the root zone to the groundwater system.

The evaporation E_{t+1}^i and the transpiration Tr_{t+1}^i in equations 3.20 and ?? respectively, are computed using the method proposed by Allen *et al.* (1998). The evaporation E_{t+1}^i is determined by multiplying the reference crop evapotranspiration $ET_{0,t+1}^i$ [mm] (computed with the FAO-Penman-Monteith equation)[11] by the evaporative coefficient $K_{e,t}^i$, which depends on $U_{1,t}^i$. The transpiration Tr_{t+1}^i instead is obtained by multiplying

$ET_{0,t+1}^i$ by two coefficients: the first is the water stress coefficient $K_{s,t}^i$, which depends on $U_{2,t}^i$; the second is the basal coefficient K_{cb}^i , which strongly depends on the crop growth stage. It follows that

$$Tr_{t+1}^i = K_{s,t}^i(U_{2,t}^i) \cdot K_{cb}^i \cdot ET_{0,t+1}^i = K_{s,t}^i(U_{2,t}^i) \cdot Tr_{pot,t+1}^i \quad (3.22)$$

Percolating water $Q_{u,t+1}^i$ and $Q_{d,t+1}^i$ are computed with the following equations:

$$Q_{t+1}^i = Q_{max,t+1}^i \cdot a \cdot e^{-d} \quad (3.23)$$

where $Q_{j,max,t+1}^i$ is computed through a simplified scheme that considers a Darcian-type flow in unsaturated soil, a is a irrigation technology-dependent coefficient and d represents the number of days since the last irrigation application (Gandolfi, 2011).

The runoff rate $Q_{r,t+1}^i$ is assumed to be null because the fields are assumed to have drainage canals.

The canopy interception is evaluated by the Braden formula (Braden, 1985), as a function of the leaf area index (LAI), the cover fraction and the volume capacity per unit foliage area, which are variables according to the crop type and the growing stage.

Estimate of the water demand of the irrigation district

The water balance just described allows the evaluation of the hydrologic balance in the root zone. The simulation of the irrigation water distribution is instead based on two conditions, which must be both met to make irrigation possible.

1. At first, the soil moisture deficit $D_{2,t}^i$ [mm], defined as the difference between the field capacity $U_{2,fc}^i$ and the soil water content $U_{2,t}^i$, is higher than the threshold value

$$D_{2,t}^i > \alpha \cdot RAW_t^i \quad (3.24)$$

where $\alpha \in [0, 1]$ ⁵ and RAW_t^i [mm] is the soil readily available water to the crop (Allen *et al.*, 1998).

2. The second condition is that the irrigation system can actually provide water to irrigate the cell, namely the volume already distributed at time t is lower than the overall volume available for irrigation for that day: $\sum_i V_{distr,t+1}^i = \sum_i (Q_{i,t+1}^i \cdot S^i) \leq V_{max,t+1}$

When $Q_{i,t+1}^i$ is non-zero, its value was assumed to be 180 mm/day for each cell in the district (the quantity averagely used for the border method). Once water is delivered to a unit, distribution within the unit takes place either on a demand basis or on a rotation basis; in the latter case, in each day a fixed number of cells is explored to check if irrigation is required and a cell is actually irrigated only if the soil water content, provided by the soil volume balance model, is such that condition 3.24 is verified. The number of explored cells is a function rotation period (turn), which is a characteristic of each unit and may vary within the district depending mainly on soil and crop types. Irrigation tail-waters from a unit are collected by the drainage network and may complement the water supply to downstream units.

In order to estimate the time-varying water demand of the whole irrigation district (which is the *deterministic scenario* that will be used to re-optimize the regulation policy in the Coupled Model), at each time t a counter records the total water volumes required by the cells of the irrigation district.

$$W_{t+1} = \sum_{i=1}^{N_{cells}} \frac{Q_{i,t+1}^i}{\eta} \quad (3.25)$$

where $Q_{i,t+1}^i$ [mm] is positive only if the two conditions above are both satisfied and η is the irrigation delivery efficiency (equal to 0.65 for sprinkler irrigation and 0.4 for surface irrigation), a parameter accounting for both conveyance and distribution efficiency in the district (remember that W_{t+1} is defined at the main canal intake).

⁵Reasonable values of this parameter should fall in the range 0.6-0.9, reflecting the precautionary point of view of farmers that require irrigation before the stress condition is reached, in order to prevent damages if the irrigation is actually available only a few days later than when the demand is expressed. Indeed, a value of 0.8 gave a satisfactory agreement between the simulated and observed values of the number of irrigations (Galelli *et al.*, 2010).

Degrees theory(Potential Heat Units) In the previous equations, the values assumed by three fundamental variables – $Z_{r,t}^i$, $K_{cb,t}^i$ and LAI_t^i – depend on crop typology and growth stage. Once these are evaluated, $ET_{0,t}$, Tr_t and $ET_{real,t}$ will be computable for each cell i and finally the actual yield per cell Y_{real} can be found through equation 3.14.

Thus, in order to evaluate $Z_{r,t}^i$, $K_{cb,t}^i$ and LAI_t^i , a model of the daily crop growth was implemented. The model is based on the concept of Growing Degrees (also known as Heat Units). Temperature is one of the most important factors governing plants' growth. Each plant has its own temperature range, i.e. its minimum, optimum and maximum for growth. For any plant, a minimum or otherwise called *base temperature* must be reached before any growth will take place. Above the base temperature, the higher the temperature, the more rapid the growth rate of the plant. Once the optimum temperature is exceeded, the growth rate will begin to slow down and will cease when the *cutoff temperature* is reached (Donatelli, 1995). The general equation used to compute the daily heat units is then

$$GD_t^i = \begin{cases} 0 & \text{if } T_{av,t}^i < T_{base} \\ T_{av,t}^i - T_{base} & \text{if } T_{base} < T_{av,t}^i < T_{cutoff} \\ T_{cutoff} - T_{base} & \text{if } T_{av,t}^i > T_{cutoff} \end{cases} \quad (3.26)$$

where $T_{av,t}^i$ is the average temperature at day t on cell i and T_{base}^i and T_{cutoff}^i [C] are respectively the base and cutoff temperature of the crop planted on cell i . The shape of the function above is shown in Figure 3.8.

The heat units theory postulates that plants growth stage is strictly dependent on the accumulated heat units $accGD_t^i$ [C] from the date of sowing to the current day t (SWAT manual, 2011), defined as follows:

$$accGD_t^i = \sum_{j=sowing^i}^t GD_j^i \quad (3.27)$$

In accordance with this theory, the database of the software IDRAGRA (Gandolfi, 2011) provides the correspondences between accumulated growing degrees $accGD_t^i$ and crop

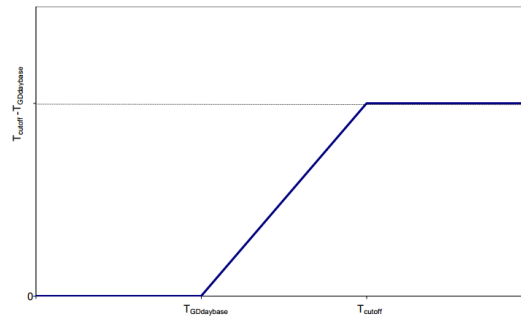


FIGURE 3.8: Graphical representation of equation ??.

parameters $Z_{r,t}^i$, $K_{cb,t}^i$ and LAI_t^i ⁶. Specifically, as the maize-related example in Figure ?? shows, the database suggests threshold values of $accGD_t^i$ and the corresponding crop parameters' values: for intermediate values of $accGD_t^i$, crop parameters are computed through a simple linear interpolation. Hence, the general shape of the function describing the evolution in time of the three crop parameters of interest becomes similar to the one visible in Figure ?? referring to the K_{cb} parameter.

Sowing date

Anyway, in order to apply equation ??, the sowing date $sowing_i$ for each cell of the space domain must be determined. According to the principles suggested in the manual of the software IDRAGRA (Gandolfi, 2011), sowing starts in the first day of the year in which the two following conditions are satisfied

- $t \geq SowingDate_{min}$
- $\frac{\sum_{j=t-4}^t T_{av,j}^i}{5} \geq T_{req}$

meaning that sowing is postponed with respect to the crop's standard sowing date $SowingDate_{min}$ until the average temperature for 5 consecutive days is higher than the crop minimum thermal requirement T_{req} (both $SowingDate_{min}$ and T_{req} are included in the IDRAGRA database).

⁶For the sake of precision, the data provided by IDRAGRA connect the accumulated growing degrees [°C] with the crop parameters, namely they allow to build the function $param = f(T)$, $param \in [Z_r, K_{cb}, LAI]$: the transposition from temperature to time domain is achieved through equation ??, which in fact can be seen as a function $T = f(t)$.

Harvesting date With the previous equations, the model describes the crop growth development happening in each cell, from sowing through the whole growing season. In order to compute the final harvested biomass that cell i produces and farmers will sell, it is necessary to define the harvesting date for each cell i , in correspondence of which equation 3.14 is applied (given the accumulated $ET_{real,tot}$ and $ET_{0,tot}$ until that moment). The harvesting date corresponds to the moment in which the crop located in cell i has accumulated a number of Growing Degrees equal to the threshold that corresponds to crop's full maturity, also known as Potential Heat Units (PHU): this is the maximum value included in the IDRAGRA files (with reference to the maize-related example in Figure ??, this threshold is 1340). In conclusion, harvesting is carried out in the first day $t : accGD_t^i \geq PHU$, where $accGD_t^i$ is computed through equation 3.27.

3.1.6 Farmer's Objective Function

The dynamical model introduced above used for Muzza region, produces outputs that are basis of construction the optimization procedure. The farmers objective is to maximize the economic revenue revenue at the end of each year, consequently suggesting new water demand for the next release policy design.

$$J_D^k = \pi \cdot \sum_{i=1}^{N_k} Y_{real}^i \quad k=1, \dots, 66 \quad (3.28)$$

where π is the price of the cultivated crop, N_k is the number of cells belonging to the k -th irrigation unit, and Y^i real the actual yield in the i -th cell. The profitability of farmers crop choices is strongly influenced by crop prices (e.g., Marques et al., 2005). However, a detailed description of market price's dynamics goes beyond the scope of this work, as it would require to model local as well as global factors (e.g., Kantanantha et al., 2010). Fixed crops prices are assumed as in Paudel and Hatch (2012), using the values published online by EUROSTAT.

3.1.7 The feedback from the farmers

Before we move towards the explaining the algorithm for solving the double problem explained above it would be interesting if we explain the feedback loop mentioned few

times before. As it was said the co crop rotation is one of the adaptive strategies that might be considered as a facing the climate change. In that sense the irrigation demand is changed according the climate changes but also the demand changes. However in this phase we will not consider adaptation strategy, so we can initially assess the impact of the climate change without any co adaptation routes, and see the possible effects on the farmers. Later we can switch towards co adaptation and compare both outputs.

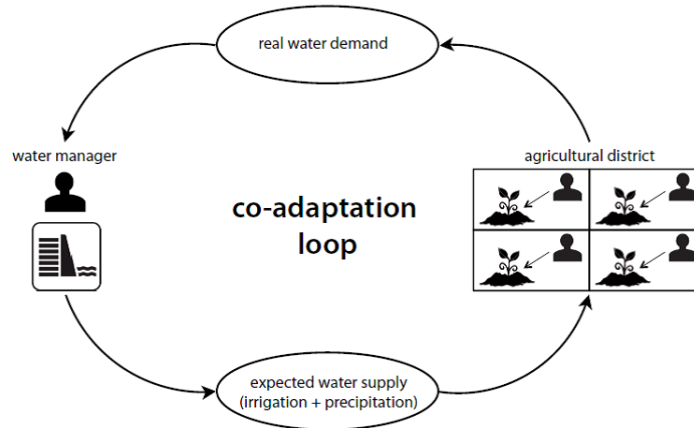


FIGURE 3.9: Adaptaion loop,with or without crop rotation

As it was anticipated in the introduction and AppendixB (MAS), and having in mind the coupled model and the figure above, it can be stated that the water supply manager is modeled as an active agent acting according to a daily operating policy p which, given the current storage of the lake st , provides the volume $u_t = mt(st)$ to be released over the time interval $[t; t + 1)$ (i.e., the next 24 hours). The optimal operating policy p is designed by formulating and solving a stochastic, periodic, non-linear, closed-loop optimal (Castelletti et al., 2008a, and references therein) of a dynamic system which evolves according to the model defined. Among the set of optimization methods available to solve the management problem formulated above, the optimal operating policy of the Lake Como is designed using stochastic dynamic programming (SDP, Bellman (1957)), as it is the most adopted and accurate method for solving optimal control problems, offering performance guarantee and proof of convergence, and explained into details in the next section. However the water demand, presumes the farmers maximum profit. Each irrigation unit, which represents the decision-making authority in charge maximizing the profit as an active agent. The optimal crop pattern can be obtained by solving non-linear optimization problems (one for each agent) based on the dynamic model of

the Muzza district described in the section below . The procedure starts by producing optimal policy for Como lake p_0 , and the a priori known demand w_0 suggested by the water manager, historical one, according his experience and to obtain the new releases r_0 . Than the crop model produces the needed irrigation water Q_i^1 for each cell and consequently the new demand w_0^{new} is reconstructed from the each cell in each time step t through the horizon of one year, adapting to the water release r_0 , in manner of producing the highest revenue. At this point, the estimate of the daily global water demand w_0^{new} becomes the deterministic scenario on the basis of which the Regulator re-optimizes the off-line reservoir release policy. The new loop starts with using w_0^{new} in order to perform the re-optimization of p_1 , and the loop goes on until it converges. In this loop new water demand w_1 is produced and that one becomes deterministic for optimizing p_2 . The convergence might be performed in two suggested ways:

1. $\sum_{t=0}^h \sum_{i=1}^{n_{c,tot}} D_{r,t,i}^* \leq a \cdot (\sum_{t=0}^h \sum_{i=1}^{n_{c,tot}} D_{t,i}^{hist})$, where the parameter $a \in [0, 1)$ can be chosen arbitrarily and $D_{r,t,i}^*$ is the estimate of the water deficit computed at time t , reiteration r and in cell i which can be computed as the difference (in each cell and for each time step) between water demand and water actually delivered: this convergence criterion stops the reiteration when the Coupled Model provides the desired reduction of the yearly district-level water deficit with respect to the one deriving from the optimization of the release policy on the basis of the historical water demand $W_{t,i}^{hist}$.
2. $n_{c,r} \leq b \cdot n_{c,tot}$, where $n_{c,c}$ represents the number of cells which were allocated to different crops in two following reiterations r and $r + 1$, $n_{c,tot}$ is the total number of cells of the space domain and b can be chosen arbitrarily.

It is useful to note that the first convergence criterion could make the model proceed to further iterations even though the crop allocation does not change, because it leads to a deficit minimization. Thus, the decision among the two criteria must be taken according to the final purpose of the project: if the requirement is to optimize as much as possible the release policy to minimize the water deficits the first criterion is suitable; in the case the final purpose of the project is to evaluate the final farmer's choices the second criterion seems instead more appropriate, because it would avoid useless

further reiterations (Matteo M.). In Appendix C there is an explanation about the co-evolutionary approach and the crop rotation.

3.1.8 The multi-objective optimization

The figure 3.1 in the beginning of this chapter clearly explain the model integration, and section 3.1.7 give a description of the off line loop, where the water regulation is actually performed by modifying the irrigation demand, introduced by the water balance module in the District model. Accordingly the water demand is no longer a scenario but an output of the model, and used in the optimization as a deterministic input. Therefore the management policy of the lake operator should be solved without any difficulty optimizing the three objective functions mentioned above, I_t^{irr} , I_t^f , $I_t^{revenue} + 1$. As the flow is explained we actually deal with 3D optimization space, but actually I revenue is optimized in one time step before. The solution leads to construction of Pareto frontier. In our case the weighted method is proposed as method determine the Pareto efficient decisions. Theoretically the optimization conditions satisfied by Pareto optimum are expressed as:

$$\sum_{i=1}^H w_i \nabla f_i(X) + \sum_{j=1}^H \lambda_j \nabla g_j(X) = 0 \quad (3.29a)$$

$$\lambda_j g_j(X) = 0, \quad \lambda \geq 0, \quad j = 1, \dots, m \quad (3.29b)$$

Where $f(X)$ is the multiple criteria, and $g(X)$, are the constraints given. What it is done is kind of a sensitivity analysis for different combinations of weights, in order to produce different point, produce Pareto front, and decide about the best mutual solution. The steps proposed for exploring the decisions are following(Zhang, 2003)[12]:

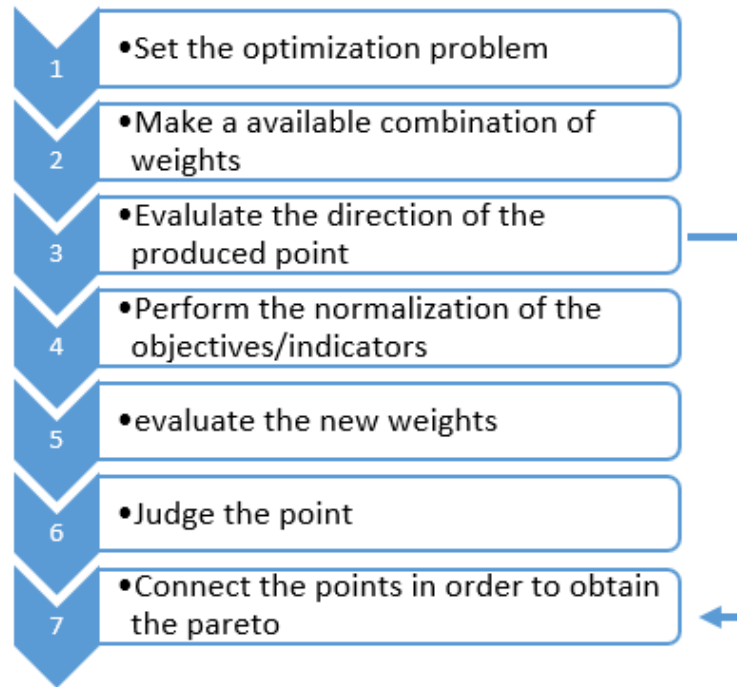


FIGURE 3.10: Wighting method steps

The weighting method introduced above is taking the multiple objectives integrating them in to one single objective giving different weight to each objective. The decision of the values of the weights is depending of the importance of the objectives and of the DM. Generally the weighted method is not a complex one and the Pareto Frontier can be constructed connecting the convex points. However this method has one major drawback : *It might skip the convex points since we connect the points that connect the concave curve line. In the figure below the point C(fig.3.11) will not be identified.*

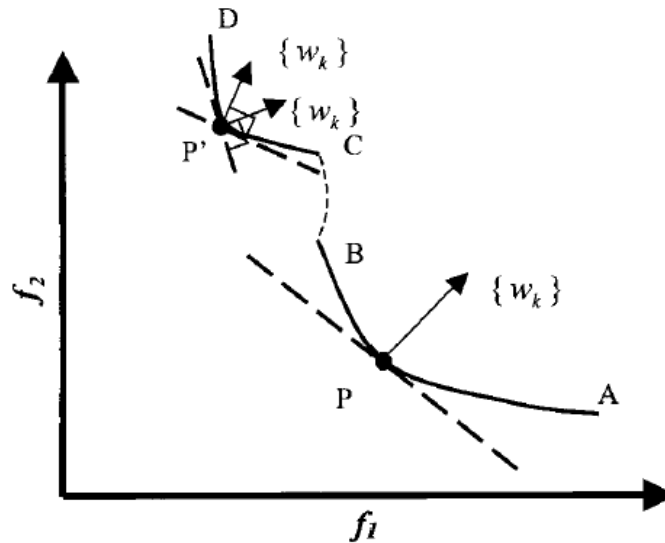


FIGURE 3.11: Designing The Pareto front, applying the weighting method, pros and cons

3.2 Climate Change(CC) scenarios

Climate change scenarios are future projected trajectories of a certain climate variable developed by different institutes. Developing of the scenarios requires estimates of future population levels, economic activity, and the structure of governance, social values, and patterns of technological change. Under CC scenarios one can consider the future emissions of GHGs. Therefore research between different groups is complementary and comparable, a standard set of scenarios are used to ensure that starting conditions, historical data and projections are employed consistently across the various branches of climate science. Socio-economic and emission scenarios are used in climate research to provide plausible descriptions of how the future may evolve with respect to a range of variables including socio-economic change, technological change, energy and land use, and emissions of greenhouse gases and air pollutants. The goal of working with scenarios is not to predict the future but to better understand uncertainties and alternative futures, in order to consider how robust different decisions or options may be under a wide range of possible futures. They are used to hand off information from one area of research to another (e.g., from research on energy systems and greenhouse gas emissions to climate modeling). They are also used to explore the implications of climate change

for decision making (e.g., exploring whether plans to develop water management infrastructure are robust to a range of uncertain future climate conditions). (AR5, IPCC). IPCC In 1996 as a response to a 1994 evaluation of the earlier IPCC IS92 emissions scenarios, the 1996 Plenary of the IPCC requested this Special Report on Emissions Scenarios (SRES). SRES scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. The IPCC SRES scenarios contain various driving forces of climate change, including population growth and socio-economic development. These drivers encompass various future scenarios that might influence greenhouse gas (GHG) sources and sinks, such as the energy system and land use change. The evolution of driving forces underlying climate change is highly uncertain. This results in a very wide range of possible emissions paths of greenhouse gases. This initiative was active until the AR4(assessment report). However, the increase of more detailed research in the different domains of climate adaptation prompted the Intergovernmental Panel on Climate Change (IPCC) to request the scientific communities to develop a new set of scenarios to facilitate future assessment of climate change (IPCC 2007). The new scenarios are called Representative Concentration Pathways (RCPs). There are four pathways RCP8.5, RCP6, RCP4.5 and RCP2.6 - the last is also referred to as RCP3-PD. (The numbers refer to forcing for each RCP; PD stands for Peak and Decline).

“The name “representative concentration pathways” was chosen to emphasize the rationale behind their use. RCPs are referred to as pathways in order to emphasize that their primary purpose is to provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. In addition, words “concentration pathway” are meant to emphasize that these RCPs are not the final new, fully integrated scenarios (i.e. they are not a complete package of socio-economic, emission and climate projections), but instead are internally consistent sets of projections of the components of radiative forcing that are used in subsequent phases. The use of the word “concentration” instead of “emissions” also emphasizes that concentrations are used as the primary product of the RCPs, designed as input to climate models...[13] They are representative in that they are one of several different scenarios that have similar radiative forcing and emissions “characteristics”. (IPCC Expert Meeting Report, Towards New Scenarios For Analysis Of Emissions, Climate Change, Impacts, And Response Strategies, IPCC 2007). “New sets of scenarios for climate change research are needed periodically to take into account scientific advances in understanding of the climate system as well as to incorporate

updated data on recent historical emissions, climate change mitigation, and impacts, adaptation, and vulnerability. The following picture(3.13) made by IPCC shows the relation of the scenarios and the potential users, modelers or developers.

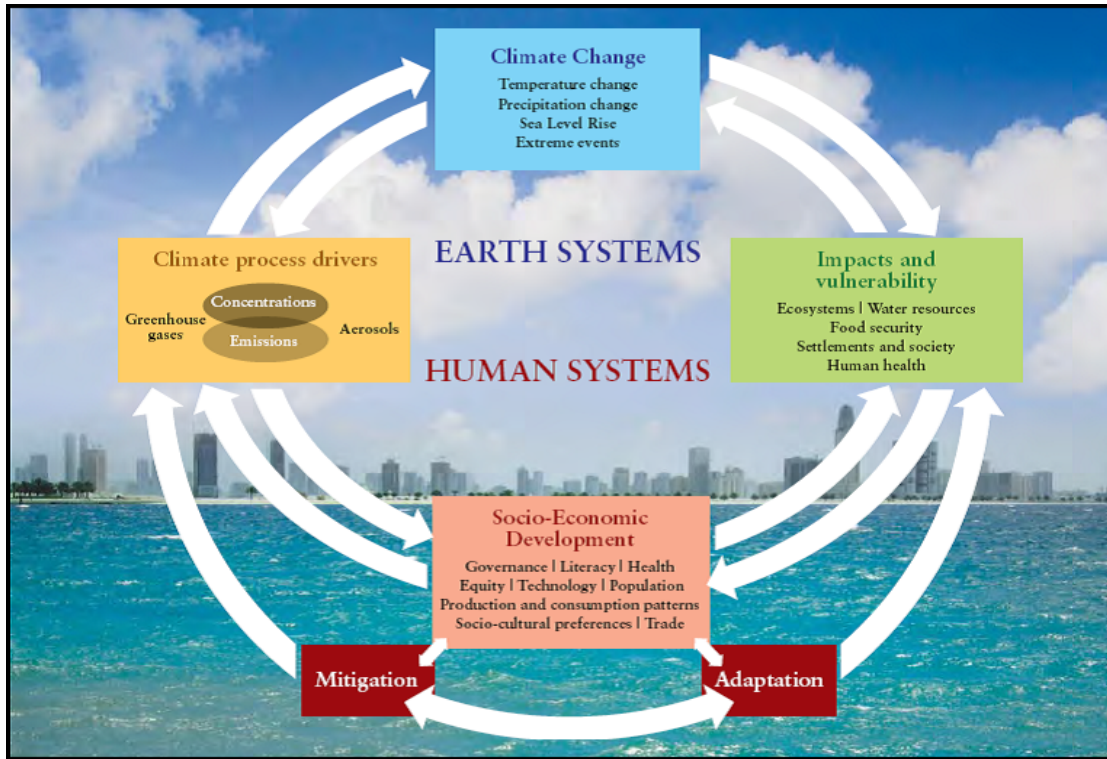


FIGURE 3.12: Actors in IPCC scenario development

Each category of emissions, an RCP contains a set of starting values and the estimated emissions up to 2100, based on assumptions about economic activity, energy sources, population growth and other socio-economic factors. (The data also contain historic, real-world information). While socio-economic projections were drawn from the literature in order to develop the emission pathways, the database does not include socio-economic data. So depending of the model requirements this data can be downloaded separately.

3.2.1 RCPs creation

Scientists always seek for improvement so the big group of researchers in IPCC is emphasizing that generally the scenarios don't just contain reference data; they also specify a process. The previous IPCC scenarios like SRES were run in sequence (see graphic below). This resulted in protracted development and delivery times. According to the

IPCC: “Lags in the development process meant that it was often many years until climate and socioeconomic scenarios were available for use in studies of impacts, adaptation, and vulnerability”.

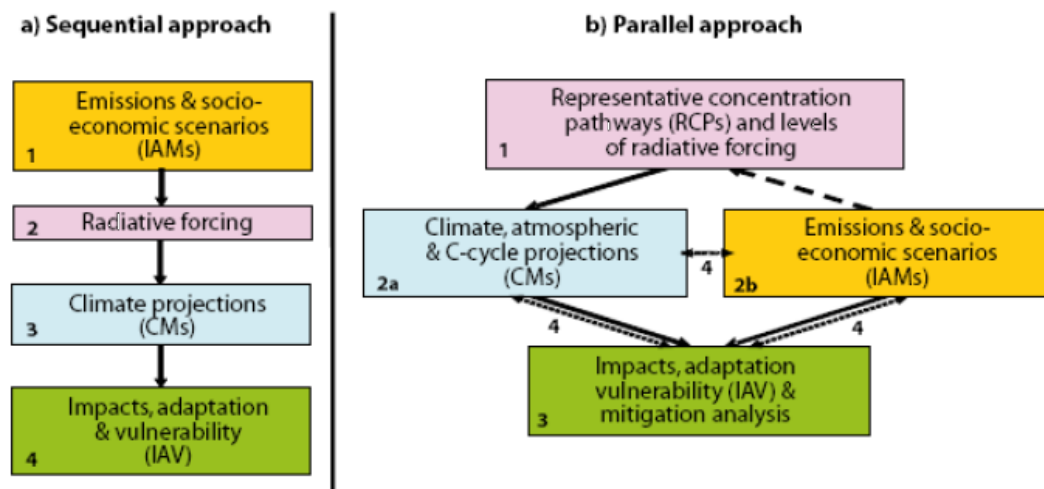


FIGURE 3.13: The approaches for emission scenarios development(right, presents brand new modified parallel Approach for Concentration pathway development, the left diagram stands for the old SERES)

As another approach that catalyze the entire process of developing these scenarios is inviting the public to participate including all possible stakeholders that may deal with them. IPCC had invited more 130 members like NGOs, government organizations and so on. Moreover the specific improvement over SERS is that RCPs instead of starting with socio-economic ”storylines” from which emission trajectories and climate impacts are projected (the SRES methodology), RCPs each describe an emission trajectory and concentration by the year 2100, and consequent forcing. Each trajectory is specific synthesis from different approaches from the literature, from this IPCC staff developed different permutations of all the social, economic technical circumstances and developed so called “narratives” instead of the old story lines.

The design criteria is made in that way that each of them represents a set of literature total literature, set of trajectories and concentration by 2100. This criteria directly follows from the purpose of the RCPs to facilitate climate model runs that are relevant for policy-making and scientific assessment (and thus cover the full uncertainty range). Another thing it was decided that the scenarios should be sufficiently separated (by about 2 Wm^2) in terms of the radiative forcing pathways to provide distinguishable climate results (Moss et al. 2008). In relation the requirements of plausibility and consistency

have been assured by basing the RCPs on published scenarios of integrated assessment models in the literature. It follows a diagram with an overview of the development process of RCPs[14].

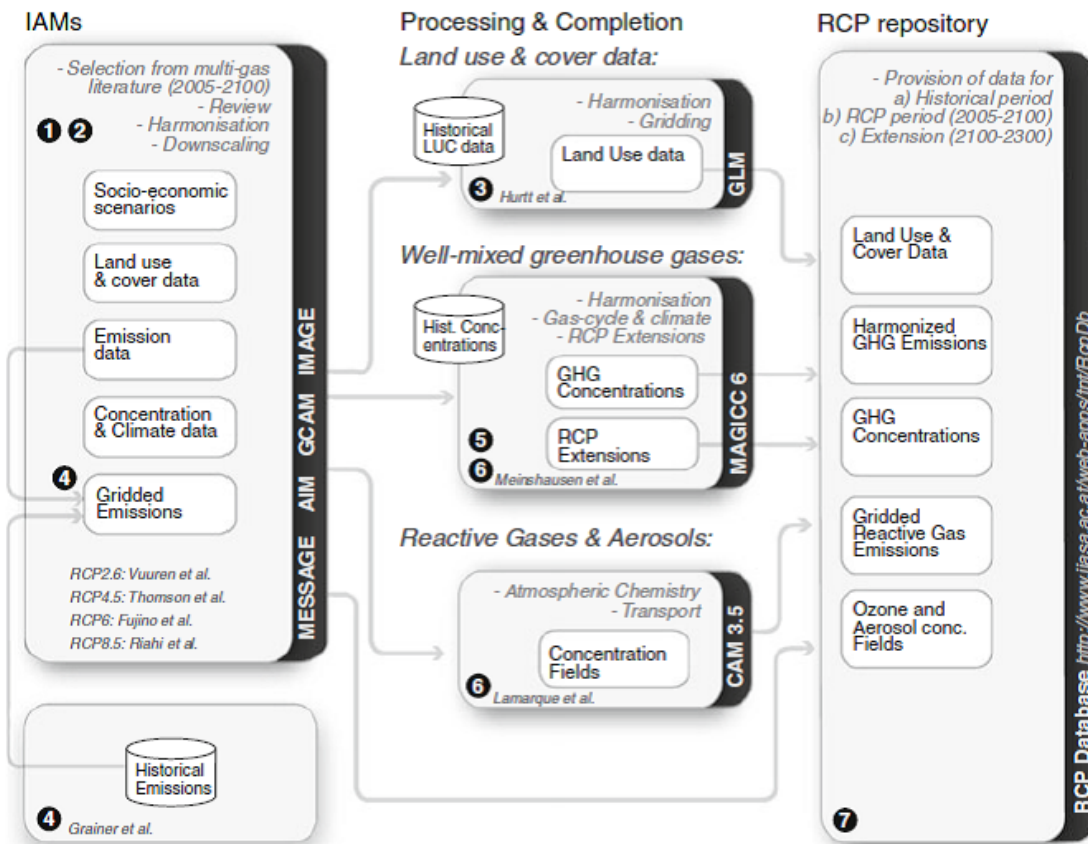


FIGURE 3.14: Diagram for Process of development of the RCPs

The development process as it can be seen above is quite complex. In relation 5 different end products are expected: Four Representative concentration pathways (The RCPs are named according to radiative forcing target level for 2100. The radiative forcing estimates are based on the forcing of greenhouse gases and other forcing agents.⁵ The four selected RCPs were considered to be representative of the literature), RCP-based climate model ensembles and pattern scaling, New IAM scenarios, Global narrative storylines, integrated scenarios. The following table give us an overview of the RCPS including the official developers.

RCP 8.5 was developed using the MESSAGE model and the IIASA Integrated Assessment Framework by the International Institute for Applied Systems Analysis (IIASA), Austria. This RCP is characterized by increasing greenhouse gas emissions over time,

TABLE 3.1: Explanation for the source and characteristics of RCPs

Pathway	Paper	Model
RCP 2.6	Van Vuuren et al. 2007a; van Vuuren et al. 2006	IMAGE
RCP 4.5	Clarke et al. 2007; Smith and Wigley 2006; Wise et al. 2009	GCAM
RCP6	Fujino et al. 2006; Hijioka et al. 2008	AIM
RCP8.5	Riahi et al. 2007	MESSAGE

Name	Radiative forcing	CO ₂ equiv (p.p.m.)	Temp anomaly (°C)	Pathway	SRES temp anomaly equiv
RCP8.5	8.5 Wm ² in 2100	1370	4.9	Rising	SRES A1F1
RCP6.0	6 Wm ² post 2100	850	3.0	Stabilization without overshoot	SRES B2
RCP4.5	4.5 Wm ² post 2100	650	2.4	Stabilization without overshoot	SRES B1
RCP2.6 (RCP3PD)	3Wm ² before 2100, declining to 2.6 Wm ² by 2100	490	1.5	Peak and decline	None

representative of scenarios in the literature that lead to high greenhouse gas concentration levels (Riahi et al. 2007).

RCP6 was developed by the AIM modeling team at the National Institute for Environmental Studies (NIES) in Japan. It is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshoot, by the application of a range of technologies and strategies for reducing greenhouse gas emissions (Fujino et al. 2006; Hijioka et al. 2008).

RCP 4.5 was developed by the GCAM modeling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI) in the United States. It is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing target level (Clarke et al. 2007; Smith and Wigley 2006; Wise et al. 2009)[15].

RCP 2.6 was developed by the IMAGE modeling team of the PBL Netherlands Environmental Assessment Agency. The emission pathway is representative of scenarios in the literature that lead to very low greenhouse gas concentration levels. It is a "peak-and-decline" scenario; its radiative forcing level first reaches a value of around 3.1 W/m² by mid-century, and returns to 2.6 W/m² by 2100. In order to reach such radiative forcing levels, greenhouse gas emissions (and indirectly emissions of air pollutants) are reduced substantially, over time (Van Vuuren et al. 2007a). (Characteristics quoted from van Vuuren et.al. 2011). From the tables above we can see the general foundation of the RCPs development and the main assumption. In the following section we are going to give the main elements that are included in the development of

TABLE 3.2: Available information form RCP and resolution

Available information from RCPs and resolution		
	Resolution (sectors)	Resolution (geographical)
Emissions of greenhouse gases		
CO ₂	Energy/industry, land	Global and for 5 regions
CH ₄	12 sectors	0.5°×0.5° grid
N ₂ O, HFCs, PFCs, CFCs, SF ₆	Sum	Global and for 5 regions
Emissions aerosols and chemically active gases		
SO ₂ , Black Carbon, Organic Carbon, CO, NO _x , VOCs, NH ₃	12 sectors	0.5°×0.5° grid
Speciation of VOC emissions		0.5°×0.5° grid
Concentration of greenhouse gases		
(CO ₂ , CH ₄ , N ₂ O, HFCs, PFCs, CFCs, SF ₆)		Global
Concentrations of aerosols & chemically active gases		
(O ₃ , Aerosols, N deposition, S deposition)		0.5°×0.5° grid
Land-use/land-cover data	Cropland, pasture, primary vegetation, secondary vegetation, forests	0.5°×0.5° grid with subgrid fractions, (annual maps and transition matrices including wood harvesting)

the RCPs and on which basis the tables of emissions are developed. If you reach the web site <http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpagepage=welcom> everyone can preview and download data on emissions, concentrations, radiative forcing and land use, in regional and gridded form, following different trajectories over similar timescales. These data sets can then be incorporated consistent foundation for all climate modelling teams anywhere in the world.

3.2.2 Global Circulation models

As we already mentioned the large amount of data developed by lead of IPCC, regarding the RCPs is mostly used in order to predict another climate variables and to develop entire simulation of future climate behavior. In this section we are going to present quickly the GCM developing procedure, without pointing out specific GCMs used by CORDEX.

GCM stands for general circulation model because it simulates the circulation of the atmosphere. GCM also can stand for global climate model. A GCM attempts to represent the climate system by calculating the properties of the Earth's atmosphere (although you could create a GCM for another planet). Examples of what makes up the climate system are shown in the picture to the right.

In other words, Numerical models (General Circulation Models or GCMs), representing physical processes in the atmosphere, ocean, cryosphere and land surface, are the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations (IPCC 2002). While simpler models

have also been used to provide globally- or regionally-averaged estimates of the climate response, only GCMs, possibly in conjunction with nested regional models, have the potential to provide geographically and physically consistent estimates of regional climate change which are required in impact analysis.

GCMs depict the climate using a three dimensional grid over the globe (see below), typically having a horizontal resolution of between 250 and 600 km, 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans. Their resolution is thus quite coarse relative to the scale of exposure units in most impact assessment. Moreover, many physical processes, such as those related to clouds, also occur at smaller scales and cannot be properly modelled. Instead, their known properties must be averaged over the larger scale in a technique known as parameterization. This is one source of uncertainty in GCM-based simulations of future climate. Others relate to the simulation of various feedback mechanisms in models concerning, for example, water vapor and warming, clouds and radiation, ocean circulation and ice and snow albedo. For this reason, GCMs may simulate quite different responses to the same forcing, simply because of the way certain processes and feedbacks are modelled. The following picture represents the above explained procedure. Actually this picture shows how in a climate model, the world is broken up into many areas. High-resolution models have millions of areas! The areas are called grid cells. Each grid cell has a location based on its position on the, earth and which vertical layer it's in.

Vertical layers are layers of air above the ground - like a bunch of blankets covering the earth one upon the other. Each "blanket" would represent a vertical layer. In a model, each layer may be a number of feet or meters thick or defined at the different pressure levels as you go higher. In the lower left of the picture you can see what actually is going on in each column of grid cells.

The exchange of heat and moisture as well as other interaction physical process, are described in details in the following picture, representing one working grid cell of the GCM.

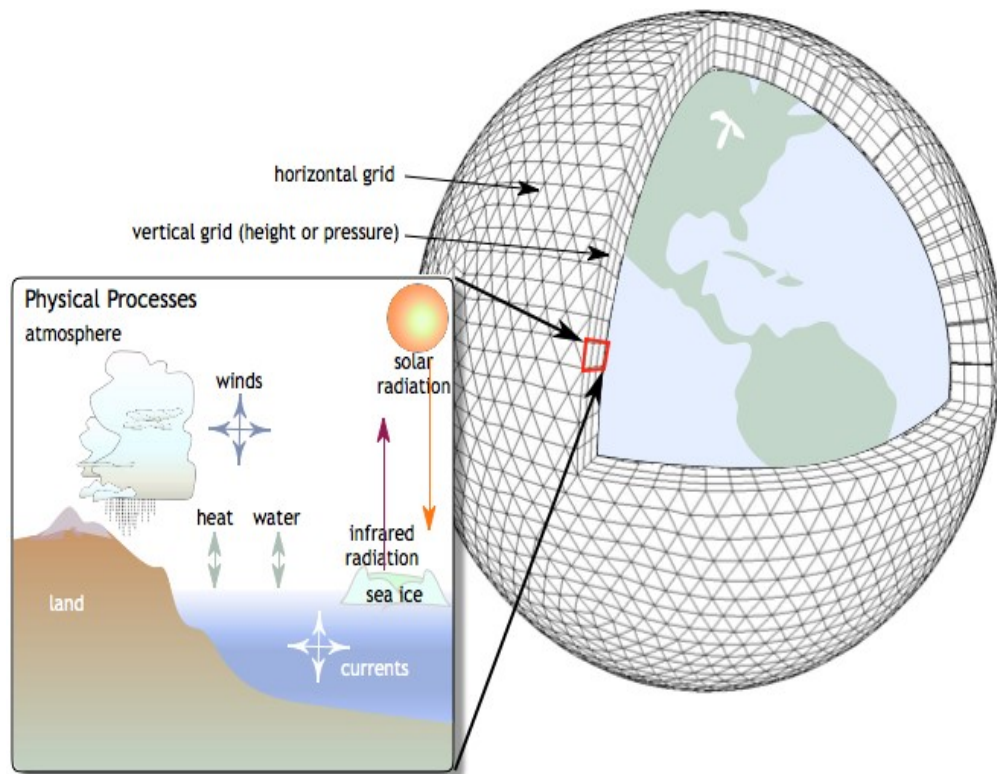


FIGURE 3.15: GCM grid cells

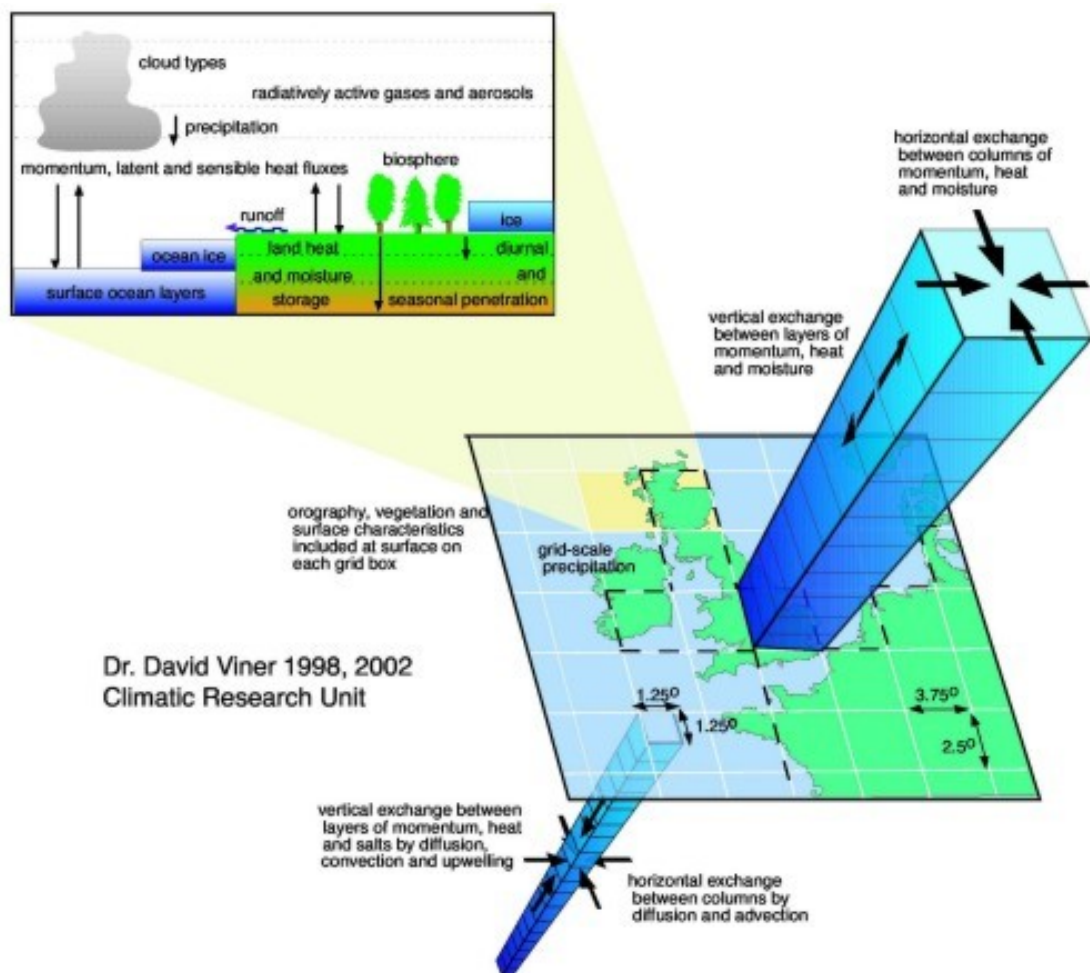


FIGURE 3.16: GCM grid cell visualization

3.2.3 Downscaling

However for local purposes (e.g. Lake Como), the data derived from GCMs is robust, coarse, thus it is needed to be adapted for regional and later local purposes[16]. For that purposes **RCM (Regional Climate Models)** are developed. In order to perform this downscaling is has to be performed. Regional Climate Models (RCMs) are used to simulate Earth's climate system at a higher spatial resolution over a limited area. Nesting a regional climate model into an existing GCM is one way to downscale data. To do this, a specific location is defined and certain driving factors from the GCM are applied to the regional climate model. A regional climate model is a dynamic model, like a GCM, but it can be thought of as being composed of three layers. One layer is largely driven by the GCM, another layer builds on some locally specific data, and the third layer uses its own physics based equations to resolve the model based on data from the other two. The results are comparatively local predictions that are informed by both local specifics and global models.

Dynamical downscaling uses a limited-area, high-resolution model (a regional climate model, or RCM) driven by boundary conditions from a GCM to derive smaller-scale information. RCMs generally have a domain area of 10⁶ to 10⁷ km² and a resolution of 20 to 60 km. Rather than using equations to bring global-scale projections down to a regional level, dynamic downscaling involves using numerical meteorological modeling to reflect how global patterns affect local weather conditions. The level of detail involved strains computer capabilities, so computations can only tackle individual GCM outputs and brief time slices. Yet climatologists generally consider three decades about the minimum for deducing climatic conditions from the vagaries of weather. The amount of computations involved in dynamical downscaling makes it "essentially impossible" to produce decades-long simulations with different GCMs or multiple emissions scenarios. As a result, most research aimed at producing regional projections involves statistical downscaling, or another approach known as sensitivity analysis to consider potential impacts on specific regions or sectors[17].

The added value RCMs are forced by time-variable conditions along the lateral atmospheric boundaries, sometimes also with large-scale constraints in the interior (von Storch et al.2000; Miguez-Macho et al. 2004; Castro et al. 2005). These constraints are taken either from global model scenarios (Christensen and Christensen 2003) or

from global reanalysis (Feser et al.2001; Sotillo et al.2005). They use high-resolution topographic details and can provide multiyear to multi decadal weather information for past or future scenarios (Jones et al. 1995, 1997; Salathé et al. 2008). In addition to prevailing large-scale conditions, local climate is influenced by regional aspects, such as local orography, land–lake contrast, and small-scale atmospheric features such as convective cells, which are not well represented in global climate models. Therefore the needed RCMs is unavoidable. Nevertheless, here we find computers as an obstacle for calculating detailed GCMs, with high resolution[18]. RCMs are therefore constructed for limited areas with a considerably higher resolution to describe regional-scale climate variability and change. During the simulations these RCMs are controlled by the global climate driving data via various mathematical routines, or dynamical downscaling.

Denis et al. (2002) developed a rather idealized way of testing the downscaling ability of nested RCMs called the Big-Brother Experiment. Instead of using data from global reanalyses, forecasts, or climate models as forcing for the RCMs, this method computes a high-resolution reference climate and then degrades it by low-pass filtering. This filtered data is then used to drive the same limited-area model. In relation with the previous section some analysis were done by Feser, Frauke Rockel and others in order to check how the dynamical downscaling of the data approximates with the local, realistic situation. An RCM should give more realistic results at medium spatial scales, for example, at 600 km and less (e.g., an RCM with a maximum grid distance of 100 km, which can resolve weather phenomena with at least four to six grid points extension). Therefore, an added value of regional climate modeling is to be expected mainly at these regional dimensions (Laprise 2003). A new concept to define potential added value (regional climate statistics have to contain some fine spatial scale variability that would be absent on a coarser grid as a necessary condition for added value) was recently introduced by Di Luca et al. (2011)[18]. RCMs are very sensitive to the physical parameterizations that are chosen (Christensen et al. 2007), which will also influence the ability of the RCM to add value. In the end of the study mostly related with the climate variables that are important for modeling the ocean behavior, some general conclusions are summarized, also important for our purposes. In addition it was shown that regional models show higher detail for mountain ranges or coastal zones, more numerous and differing vegetation and soil characteristics, and a description of smaller-scale atmospheric processes, which lead to the formation of mesoscale weather phenomena. These RCM characteristics are believed to produce model output that is closer to reality than the more coarsely resolved global

model data, both for reanalyses for hindcast studies, and for global scenario simulations. In the mentioned study it was discovered that dynamical downscaling does not add value to global reanalysis wind speed in open ocean areas, while it does for complex coastal areas. The regional model needs the higher-resolved orography or coastlines to achieve more realistic results than the already well described global reanalyses for near-surface wind speed. Regional models show an added value in describing mesoscale variability compared to the driving global reanalysis, in particular, when the RCM is constrained at the large spatial scales. This is more obvious for variables, such as near-surface temperature, that are more heterogeneous than sea level pressure. Also Regional Climate Model simulations provide higher daily precipitation intensities, which are completely missing in the global climate model simulations, and they provide a significantly different climate change of daily precipitation intensities resulting in a smoother shift from weak to moderate and high intensities. Finally it can be said that RCMs do indeed add value to global models for a number of applications, variables, and areas. If examined only at the regional scale, added value emerges very distinctly for many model variables, justifying the additional computational effort of RCM simulations. ("Value to Global Model Data: A Review and Selected Examples" Feser, Frauke Rockel, Burkhardt von Storch, Hans Winterfeldt, Jörg Zahn, Matthias)[16, 19].

3.2.3.1 CORDEX data

Relying on the experts suggestions for this study the EURO CORDEX scenarios are chosen as the representative ones. EURO CORDEX initiative assumes more than 50 GCM/RCM combinations regarding different RCPs. Therefore after the explanation of the dynamical downscaling we will pay attention to the chosen combination of RCMs and few comments about EURO CORDEX. CORDEX is an experimental framework for assessing regional climate change, with particular emphasis on the comparison, evaluation, documentation and improvements on Regional Climate Downscaling (RCD) techniques and on the support to regional capacity building. EURO-CORDEX is the European branch of the international CORDEX initiative, which is a program sponsored by the World Climate Research Program (WRC) to organize an internationally coordinated framework to produce improved regional climate change projections for all land regions world-wide. The CORDEX-results will serve as input for climate change impact and

adaptation studies within the timeline of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) and beyond.

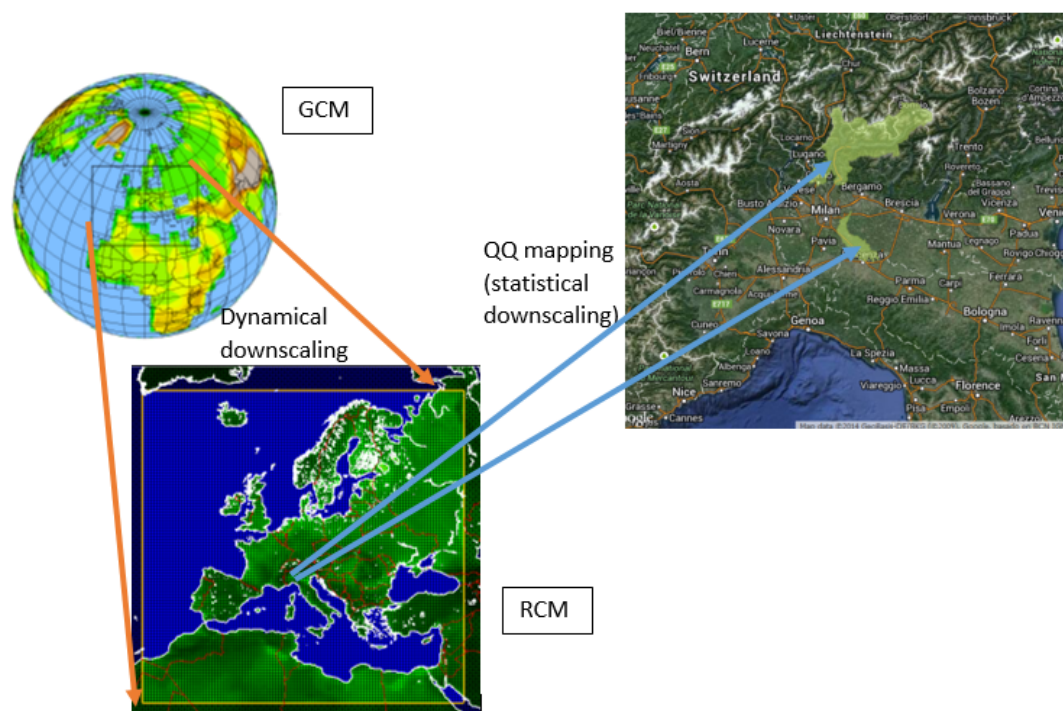


FIGURE 3.17: Downscaling flow scheme

The CORDEX regional climate model (RCM) simulations for the European domain (EURO-CORDEX) are conducted at two different spatial resolutions, the general CORDEX resolution of 0.44 degree (EUR-44, 50 km) and additionally the finer resolution of 0.11 degree (EUR-11, 12.5km). Accordingly to the previous discussed section about RCPs, CORDEX uses those emission scenarios as representative ones (rcp26 rcp45 rcp85). In fact this international project in coordination with many worldwide institutes develop RCMS frameworks that has been used to downscale a subset of Global Climate Models (GCMs) simulations from the 5th Coupled Model Intercomparison Project (CMIP5). Future climate projections from nine CMIP5 GCMs, under both the RCP4.5 and RCP8.5 scenarios, have been downscaled in different combinations over 6 of 13 CORDEX domains: Africa, Europe, Arctic, Middle East and North Africa (MENA), South Asia and South America. One RCP2.6 scenario from EC-EARTH has also been downscaled for the 6 CORDEX domains chosen. In the Chapter 4?? we offer a table with all the models downscaled and the institution referring to them. The data developed under the EURO CORDEX project is published via Earth System Grid Federation (ESGF) Peer-to-Peer

(P2P) under the same project name "CORDEX". There the downloading procedure of around 1 TB was performed. For the purposes of the models just precipitation and average surface temperature we needed to be downloaded. The data downloaded was in nested in NETcdf format in different tables, thus MatLab netcdf tools were use in order to preprocess the data and prepare matrices as INPUT files for the 3 different models mention in the chapter above. In addition it is obvious that Euro CORDEX covers spatial domain of entire Europe, so another task was related with cutting the region of interest. And therefore performing Thissen method for the precipitation since the observation data is available only as areal average precipitation of the Como catchment area. During the data analyzing some model were discarded found as not reliable and not complete. For example the Model referring to the RCM MOHC were not complete simulating 360 days per year, including the fact that one month is missing from the RCP45 emission scenario. Different resolution for different pathways were located in MPI(GCM) RCA4(RCM), plus precipitation missing in the lower resolution. The next phase is including statistical downscaling, better correcting the regional back cast downscaling data and the observations so we can approach towards more realistic values. This point out that value is added to the RCMs as well. For the purposes of this study we

offer the following downloaded combinations:

TABLE 3.3: Table of EUROCORDEX downloaded scenarios

name of the files: VariableName_Domain_GCMModelName_CMIP5_ExperimentName_CMIP5_RCMMModelName.mat								
Project	RCM(Regional ClimateModel)	GCM(Global ClimateModel)	Exp.combination	time	variable short name	ensemble	#outputs	domain
C O R D E X	RCA 4	ICHEC-EC-EARTH	rcp26	1 DAY	ts and pr(P_areal)	r1i1p1	1	EUR-11
	CCLM4	CNRM-CERFACS-CNRM-CM5	rcp45		ts and pr(P_areal)	r1i1p1	1	EUR-11
		MPI-M-MPI-ESM-LR	rcp45		ts and pr(P_areal)	r1i1p1	1	EUR-11
	HIRHAM5	ICHEC-EC-EARTH	rcp45		ts and pr(P_areal)	r3i1p1	1	EUR-11
	RACMO22E	ICHEC-EC-EARTH	rcp45		ts and pr(P_areal)	r1i1p1	1	EUR-11
	RCA4	CCCma-CanESM2	rcp45		ts and pr(P_areal)	r1i1p1	1	EUR-44
		CNRM-CERFACS-CNRM-CM5	rcp45		ts and pr(P_areal)	r1i1p1	1	EUR-11
		ICHEC-EC-EARTH	rcp45		ts and pr(P_areal)	r12i1p1	1	EUR-11
		IPSL-IPSL-CM5A-MR	rcp45		ts and pr(P_areal)	r1i1p1	1	EUR-44
		MIROC-MIROC5	rcp45		ts and pr(P_areal)	r1i1p1	1	EUR-44
		NCC-NorESM1-M	rcp45		ts and pr(P_areal)	r1i1p1	1	EUR-44
		NOAA-GFDL-GFDL-ESM2M	rcp45		ts and pr(P_areal)	r1i1p1	1	EUR-44
	REM2009	MPI-M-MPI-ESM-LR	rcp45		ts and pr(P_areal)	r1i1p1	1	EUR-11
	CCLM4	CNRM-CERFACS-CNRM-CM5	rcp85		ts and pr(P_areal)	r1i1p1	1	EUR-11
		ICHEC-EC-EARTH	rcp85		ts and pr(P_areal)	r1i1p1	1	EUR-11
		MPI-M-MPI-ESM-LR	rcp85		ts and pr(P_areal)	r1i1p1	1	EUR-11
	HIRHAM5	ICHEC-EC-EARTH	rcp85		ts and pr(P_areal)	r3i1p1	1	EUR-11
	RACMO22E	ICHEC-EC-EARTH	rcp85		ts and pr(P_areal)	r1i1p1	1	EUR-11
	RCA4	CCCma-CanESM2	rcp85		ts and pr(P_areal)	r1i1p1	1	EUR-44
		CNRM-CERFACS-CNRM-CM5	rcp85		ts and pr(P_areal)	r1i1p1	1	EUR-11
		ICHEC-EC-EARTH	rcp85		ts and pr(P_areal)	r12i1p1	1	EUR-11
		IPSL-IPSL-CM5A-MR	rcp85		ts and pr(P_areal)	r1i1p1	1	EUR-11
		MIROC-MIROC5	rcp85		ts and pr(P_areal)	r1i1p1	1	EUR-44
		MOHC-HadGEM2-ES	rcp85		ts and pr(P_areal)	r1i1p1	1	EUR-11
		MPI-M-MPI-ESM-LR	rcp85		ts and pr(P_areal)	r1i1p1	1	EUR-11
		NCC-NorESM1-M	rcp85		ts and pr(P_areal)	r1i1p1	1	EUR-44
	NOAA-GFDL-GFDL-ESM2M	rcp85	ts and pr(P_areal)		r1i1p1	1	EUR-44	
	REM2009	MPI-M-MPI-ESM-LR	rcp85		ts and pr(P_areal)	r1i1p1	1	EUR-11 -1
total outputs							29	
Historical								
Project	Model	Driving Model	Exp.combination	time	variable long name	ensemble	#outputs	domain
C O R D E X	CCLM4	CNRM-CERFACS-CNRM-CM5	historical	1 DAY	ts and pr(P_areal)	r1i1p1	1	EUR-11
		ICHEC-EC-EARTH	historical		ts and pr(P_areal)	r12i1p1	1	EUR-11
		MPI-M-MPI-ESM-LR	historical		ts and pr(P_areal)	r1i1p1	1	EUR-11
	HIRHAM5	ICHEC-EC-EARTH	historical		ts and pr(P_areal)	r3i1p1	1	EUR-11
	RACMO22E	ICHEC-EC-EARTH	historical		ts and pr(P_areal)	r1i1p1	1	EUR-11
	RCA4	CCCma-CanESM2	historical		ts and pr(P_areal)	r1i1p1	1	EUR-44
		CNRM-CERFACS-CNRM-CM5	historical		ts and pr(P_areal)	r1i1p1	1	EUR-11
		ICHEC-EC-EARTH	historical		ts and pr(P_areal)	r12i1p1	1	EUR-11
		IPSL-IPSL-CM5A-MR	historical		ts and pr(P_areal)	r1i1p1	2	EUR-11 EUR-44
		MIROC-MIROC5	historical		ts and pr(P_areal)	r1i1p1	1	EUR-44
		MPI-M-MPI-ESM-LR	historical		ts and pr(P_areal)	r1i1p1	2	EUR-11 EUR-44
		NCC-NorESM1-M	historical		ts and pr(P_areal)	r1i1p1	1	EUR-44
		NOAA-GFDL-GFDL-ESM2M	historical		ts and pr(P_areal)	r1i1p1	1	EUR-44
	REM2009	MPI-M-MPI-ESM-LR	historical		ts and pr(P_areal)	r1i1p1	1	EUR-11 -1
total outputs							16	

3.2.3.2 Statistical downscaling (QQ mapping)

Providing user-tailored adequate (bias free) climate information for our local purposes and the hydrological model described above empirical statistical downscaling of the already downscaled RCMs is required.

Empirical-statistical downscaling (ESD) is a method for estimating how local climatic variables are affected by large-scale climatic conditions. The essence of ESD is to identify synchronized or "matching" time behavior on large- and small scales, hence practical ESD focuses on the time dimension. One of the primary advantages of these techniques is that they are computationally inexpensive, and thus can easily be applied to output from different GCM experiments. Another advantage is that they can be used to provide local information, which can be most needed in many climate change impact applications.

In addition, empirical downscaling methods often offer a framework for testing the ability of physical models to simulate the empirically found links between large-scale and small-scale climate (Busuioc et al., 1999; Murphy, 1999; Osborn et al., 1999; von Storch et al., 1993; Noguer, 1994)[19]. However the major theoretical weakness of statistical downscaling methods is that their basic assumption is not verifiable, i.e., that the statistical relationships developed for present day climate also hold under the different forcing conditions of possible future climates. Several methods for statistical downscaling are offered like: delta change methods, unbiased methods, neural networks, analogues methods, weather methods, quintile mapping, etc.

One of the most often used method is called **Quantile Mapping (QM)**. Quantile mapping is routinely applied to correct biases of regional climate model simulations compared to observational data. If the observations are of similar resolution as the regional climate model, quantile mapping is a feasible approach. However, if the observations are of much higher resolution, quantile mapping also attempts to bridge this scale mismatch. **Q-Q** plots are graphical representation of this method, which compare the probability distribution of two variables, by representing on a Cartesian plane some quantiles of a variable against those of another variable or a theoretical distribution.

Speaking of QM we can define few advantages of its common use:

- Fits properly the variables from GCM/RCM to the observed distribution.

- One of the simplest, most successful, most flexible methods (applies to different variables).
- Can correct the shape of the distribution, including extremes.
- As mentioned before, temporal autocorrelation properties of the RCMs time series are not corrected (e.g. length of dry spells)

For purposes of the explanation of the process of QQ mapping we are going to define the following variables:

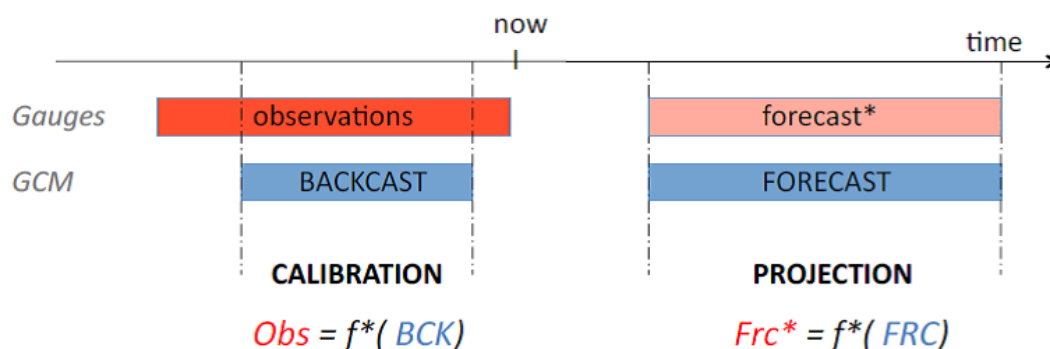
X- predictor, large scale, **BCK**

y=f(X)

y- predictant, small scale, **Obs**

The predictand (Y) is any variable, in our case precipitation and temperature needed for purposes of local hydrologic modeling. Usually the predictor and the predictant are the same variables. If x is output of RCM we obtain downscaling and bias correction. This statistical downscaling consist of two phases:

1. I. Calibration: the relation $y=f(x)$ is estimated using the backcast data from the RCMs and the historical observation, taken from specific station. Here one should pay attention that the station is chosen according the proximity to the grid point of the model variable.
2. II. Projection: in the previous case the model for downscaling(QM) is trained, the parameters are obtained and now the future observation from the RCMs are corrected, downscaled as well, performing new operation f^*



Therefore the downscaling of the scenario MPI REMO2009, taking precipitation as variable is presented through the graphs below:

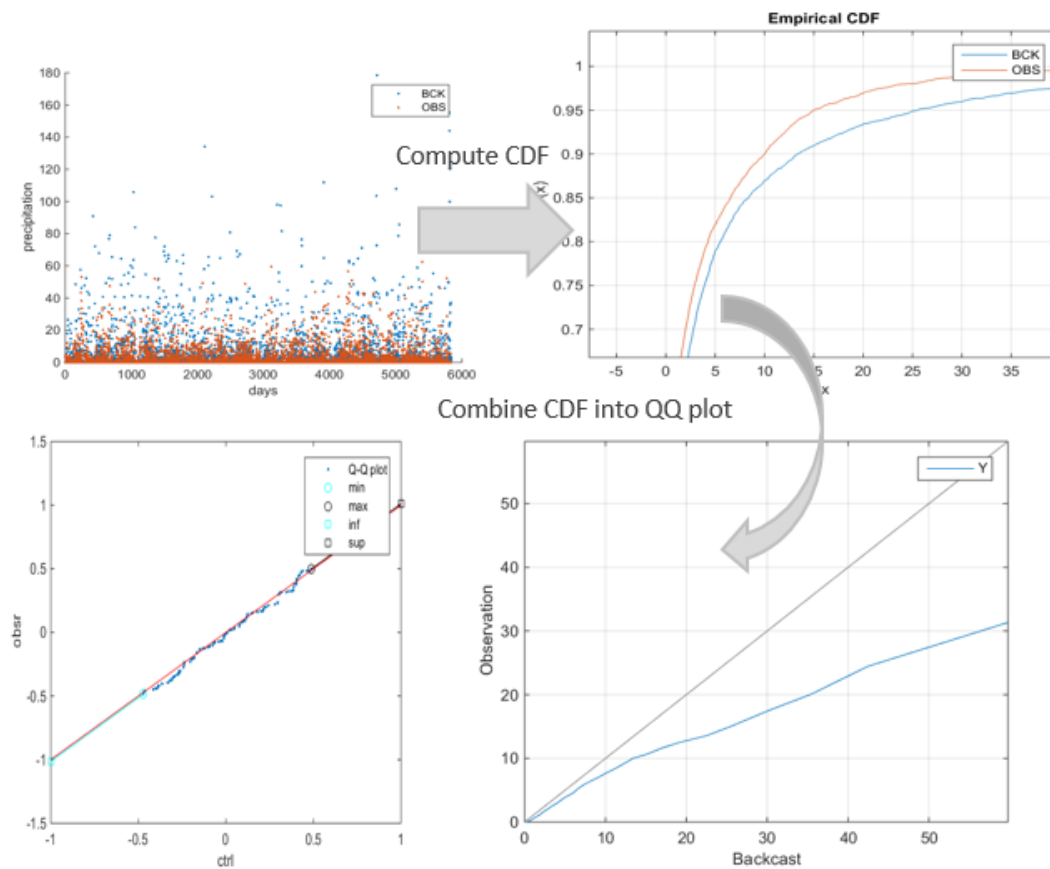


FIGURE 3.18: QQ mapping downscaling steps

As it can be seen from the graphs 3.18 obviously we deal with scenario overestimation of the precipitation, since the QQ plot is skewed on the right, after downscaling. This is kind of expected since the GCMs are developed for future predictions and calibrated for a control period of next 100 years. In that sense we cannot expect data matching between the backcast and the historical precipitations. In the following figure 3.19 we can conclude the opposite happening with the temperature.

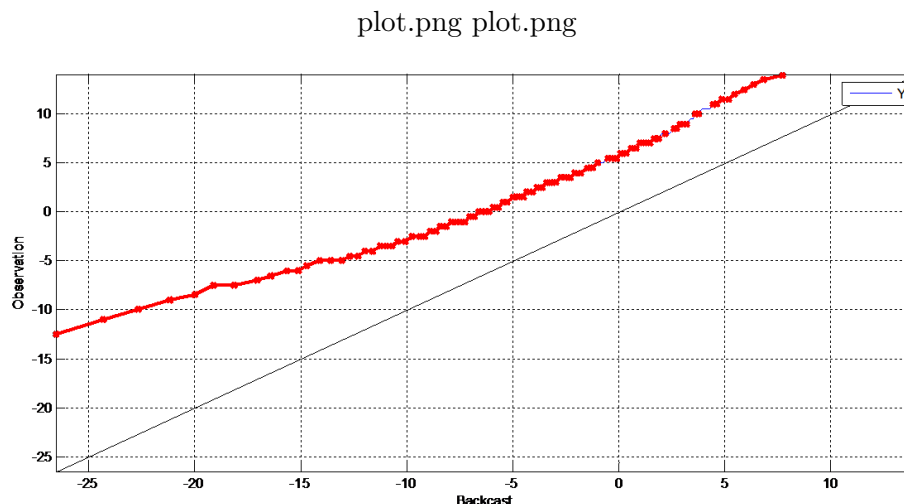


FIGURE 3.19: Output from the QQ downscaling, temperature underestimating the real observations

Some additional remarks on QM are given:

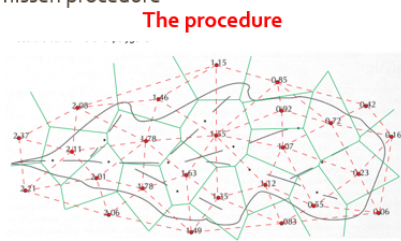
- QQ plot consist of plotting the observed values against model values, both corresponding to same probability .
- If the backcast is the same as the observation, than the curve is 45 degrees straight line. QQ plots is equivalent to suppose that RCMs is able to predict a ranked category, but not the precise value.

Regarding the data required to run the Lake/District model and the rainfall/runoff HBV, two different regions of data are cut and downscaled:

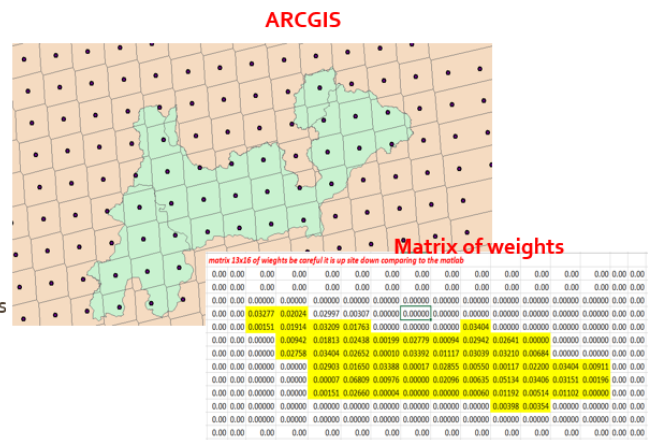
1) *Como catchment area.*

Downscaling was performed in two different ways for precipitation and temperature according the available measured data. The available data was from 1965 till 1980 daily measurements, with no missing observations. The precipitation was downscaled in a way that firstly on the cut region Thissen method was performed using ARCGIS. Except that procedures of intersecting, creating new feature layers was performed. Later the weighted matrix was realized in well-known way, as in the end the areal precipitation to be estimated.

Thissen procedure



What you actually do is merging the gauge points of precipitation from the model into areal precipitation for the entire catchment using Voronoi polygons. → you obtain **one column** matrix that is the **required INPUT** for both the models



The temperature was easily downscaling, taking the average values from the observation measured in station Cancano, since the models values are mean surface temperature.

2) *Muzza region*

For the requirements of the District model, we need data from three different stations. In order to perform the downscaling we choose the nearest points from the scenarios, or using the proximity theory in order to have the closest possible spatial accuracy. The downscaling was performed in the explained way taking the observation from the stations.

3.3 General information on uncertainty

Uncertainty in the words of Galbraith (1973) is the difference between the amount of information required to perform a task and the amount of information already possessed. In my point of view uncertainty serve as an after effect of a present happening but a predicted situation of unknown occurrences which can brought positive or negative outcome.

Hydrological models are simplified representations of natural processes, which are constituted by input variables; a processing box – that mimics hydrological processes through a set of equations aimed at matching the observed and simulated values by a set of parameters-, and output variables. However, the incompleteness of knowledge about the state or process being modeled is defined as uncertainty (Caddy and Mahon, 1995). As noted by Brazier et al. (2000), estimating uncertainty is not just a way to look

for weaknesses in the model, it is a way to improve the model. Therefore, uncertainty should be estimated by modelers and communicated to the end-users.

When confronted with assembling data and information to support the decision-making process there is a need to understand its nature and how it can and should not be used. One aspect of particular interest is that for all data and information there are associated uncertainties. The nature and extent of these uncertainties should be considered when deciding how to use any data and information, and the types of decision that can be drawn. As it is well known the uncertainty describes a condition where we lack certain knowledge that we think may be important to making a decision. Where we know the probability associated with a particular rainfall event and the consequences of the event, but not when or where such an event will occur, that is risk. Where we do not know the probability and/or the consequence, that is uncertainty. Hence we are confident in our knowledge that the climate is changing (IPCC 2001a, p.4) but our knowledge of the precise nature, extent and rate of these changes is imperfect or limited.

A natural reaction when confronted with such uncertainties (e.g., uncertainties in climate information in our case) is to provide the information to improve knowledge and understanding, and to provide, more accurate forecasts of future conditions. According some suggestions of experts and experience as well as comprehensive research the usage of CORDEX scenarios was the most appropriate among. Unfortunately, even though knowledge will improve, uncertainty will remain inherent and therefore needs to be considered in adaptation decision making. Nevertheless, we may be able to estimate or understand the consequences of particular events, even though we are uncertain as to their likelihood – we are confident of the outcomes, but uncertain or ignorant of the probability of their occurrence. Vulnerability studies aim to determine how sensitive or how vulnerable a receptor is to a particular hazard. In such studies we effectively analyze a scenario that assumes that a particular hazardous event may occur, and determine the likely consequences. For example, the consequences of flooding are well known. Hence the consequences of an increase in flood frequency and magnitude can be determined with considerable confidence, even if the probability of such an event is itself very uncertain.

Since we are dealing with co adaptation problem and optimization, the highlight of importance is to understand the uncertainty in order to be able to:

Reduce it and,

Ensure its reflection to the decision making process.

3.3.1 Sources of uncertainty

A wide range of data is used in the process of co adaptation of the Muzza irrigation district. The precipitation and surface temperature, or the climate data is just one type of the data used in the sequence of the models. As with any data and information, particularly when it has been derived from models, there are associated uncertainties that those using the data and information should be aware of. The uncertainties result from a number of sources. Some of these uncertainties have to do with imperfect knowledge while others relate to the intrinsic variability in the climate, economic, social and environmental systems. There will always be an element of uncertainty to adaptation planning and decision-making. Adaptation to climate change presents a complex methodological challenge. It calls for individuals to make decisions with potentially long term consequences on the basis of incomplete knowledge and uncertain information. There are numerous sources of uncertainty that need to be considered, such as social, economic and technical trends as well as potential changes in the legal, fiscal and regulatory system. There are also uncertainties associated with the assessment of current vulnerabilities to the impacts of climate variability and identifying and evaluating adaptive responses. Dealing with uncertainty in the water resources management heartlessly lead to uncertainty sources over-crossing. I.e. if you want to consider natural variability it automatically corresponds to modeling uncertainty since we describe physical systems that have to include natural variation of the parameters. The socio- economics is included into seeking the optimality, and into MAS construction, hence we deal with stakeholders interests. The uncertainty can be categorized in three groups:



FIGURE 3.20: Sources of Uncertainty

The *first* one comes from the **Input data** and it does not depend of the performance of the model. Therefore, this one includes the uncertainty coming from:

- *Inherent and natural internal variability*

The world we live in is characterized by events that, despite perfect knowledge, can only be described probabilistically (pure "risk"). For example, life expectancy can only be described statistically as the probability (or risk) of surviving to a particular age, or dying of a particular cause[20]. Many environmental processes possess these statistical characteristics, reflecting essentially random processes that govern particular events. For practical purposes this includes the weather and climate, which are variable over all spatial and temporal scales. Weather, for example, cannot be predicted reliably more than a few days in advance. There is uncertainty in the timing, duration, spatial location, extent and other characteristics of weather 'events' such as droughts, cold spells and storms. So, while it may be possible to estimate the probability and magnitude of a particular event (such as a flood)[21] that is likely to occur within the next 20 years, it is not possible to say whether this will occur in 2003 or 2023.

- *Data uncertainty*

Data uncertainty arises because of: measurement errors, incomplete, missing data, extrapolation based on the uncertain data. This uncertainty is related with the calibrating the models or downscaling the future scenarios for a certain region.

In our case there are lot of parameters, data and other information that derive amount of uncertainty. Any way as it can be seen from the modeling procedure the uncertainty form the climate data is the most important since it is a key data in the co adaptation. This leads to the fact the among the lot of data like radiation, wind speed, Bellman series, and so on we will focus on the precipitation and surface temperature as the main sources of Input uncertainty. The uncertainty coming out from the water demand and the social and spatial development of the cities is not considered or it is constant.

The *second one* is uncertainty produced by the models and their performance. It is strongly related with structure of the model, type of the model, and of the parameters that have to be calibrated. In fact the incompleteness of knowledge about the state or process being modelled is defined as uncertainty (Caddy and Mahon, 1995). Models uncertainty includes:

- Models choice and structure: Any different structure, even producing the same effect causes slight change in to the output variables.
- Models input values: This consequently correlates to the previous type of uncertainty.
- Model parameters: Many parameters are estimate from a limited data of uncertain quality.
- Model output values: The consequences of model uncertainties for model output variables can be determined to a certain extent using methods of uncertainty and sensitivity analysis (Saltelli et al, 2001). Output variables frequently become the inputs to the next stage of the impact assessment, so the uncertainty propagates through the assessment process.

There are different methodologies in order to decrease the uncertainty produced by the model itself. Ones focuses on the set of parameters (Uncertainty estimation GLUE), others focuses on the model development.

For most real-world decisions the available theoretical and empirical knowledge is unlikely to provide complete, sufficient, or even partial understanding of the problem facing the decision-maker. Based on the information from the previous two the third one is naturally followed by the method of optimization and the subjective attitudes of the decision maker. Eventually we can conclude that all of these uncertainties are cross correlated. In fact the first one is related due to the fact that some input data are produced by models (e.g hydrological models). The model uncertainty is specific case of knowledge or modeler experience or decision maker subjectivity itself, as they are making the final decision for the type of the model.

In the end we can conclude that classifying uncertainty is not an easy task. If we follow Norton et al. (2005) a basic distinction can be made between quantifiable and non-quantifiable uncertainty.

Quantifiable uncertainties are those associated to the values:

- of the system variables;
- of the parameters appearing in the model of the system and of the parameters appearing in the functions used to compute indicators and indices.

Note that a difference exists between the uncertainty associated to the variables and parameters appearing in the model of the physical system (A and B) and the uncertainty associated to the parameters appearing in the definition of indicators and indices (C). The quantification of the first type of uncertainty is somehow "objective": it is based on the comparison between the values of the system variables computed with the model of the physical system and those measured in reality. Here, uncertainty is due to a lack of capability in modeling the system, i.e. it expresses the error that is made in assuming an approximate description of reality. Instead, the quantification of the second type of uncertainty, associated to the definition of indicators and indices, is "subjective": we know that our synthesis of the physical effects on the system (i) and of the satisfaction of each DM (I) is not perfect, but we do not know what the "exact" values of i or I should be. In relation with parameters uncertainty sensitivity analysis is the most suitable tool for assessing. The same stands for assessing the indicators and indices.

Not quantifiable uncertainties are those associated to the choice of the model, of the functionals used to compute the indicators, of the evaluation and comparison method. Describing this type of uncertainty is very difficult and constitutes a challenge for future research (Maier and Ascough II, 2006). One possible way to assess the impact of non quantifiable uncertainty on the decision is that of repeating the decision-making procedure while changing some assumptions (e.g. using a different definition of the indicators, a different model or evaluation method) and check whether results change and how. Note that this can be seen as a sort of non-automatized (trial-and-error) version of sensitivity analysis (RSS, AC, IPWRM).

3.4 Uncertainty in the climate information

The focus of this thesis will be on the climate change information, moreover dealing with the different scenarios in order to understand the uncertainty caused by them. In the beginning we have to explain and understand the uncertainty of the climate change information itself. In this section the explained uncertainty above is just focused towards climate change scenarios. Uncertainty in climate information stems the natural variability inherent in the climate system and from limitations in our ability to model the climate system and in our understanding of how future greenhouse gas emissions will change. Our understanding and modeling of climate change has advanced significantly

in recent decades and increased the confidence we can place in the projected changes that are likely for key climate variables such as temperature, sea-level rise, snow cover, and the risk of heat waves and drought. There is also an improving understanding of projected patterns of precipitation which suggest that patterns observed in recent trends are likely to continue. Generally, there is greater confidence in projections for larger regions than for specific locations, in temperature projections than those for precipitation, and for gradual changes in average conditions than we can have for extreme weather events such as storms. These characteristics of the projections present challenges to adaptation planning but they do not mean that adaptation is impossible or cannot be addressed. Instead, adaptation planners need to understand the information that is available, including the associated uncertainties at different temporal and spatial scales and consider what that uncertainty means for decision-making. They also need to ensure that the uncertainties and implications for the resulting decisions are clearly communicated, particularly in the context of supporting, evaluating and updating adaptation actions and plans. Uncertainties in climate change information arises from three primary sources:

„Chain of Uncertainty“

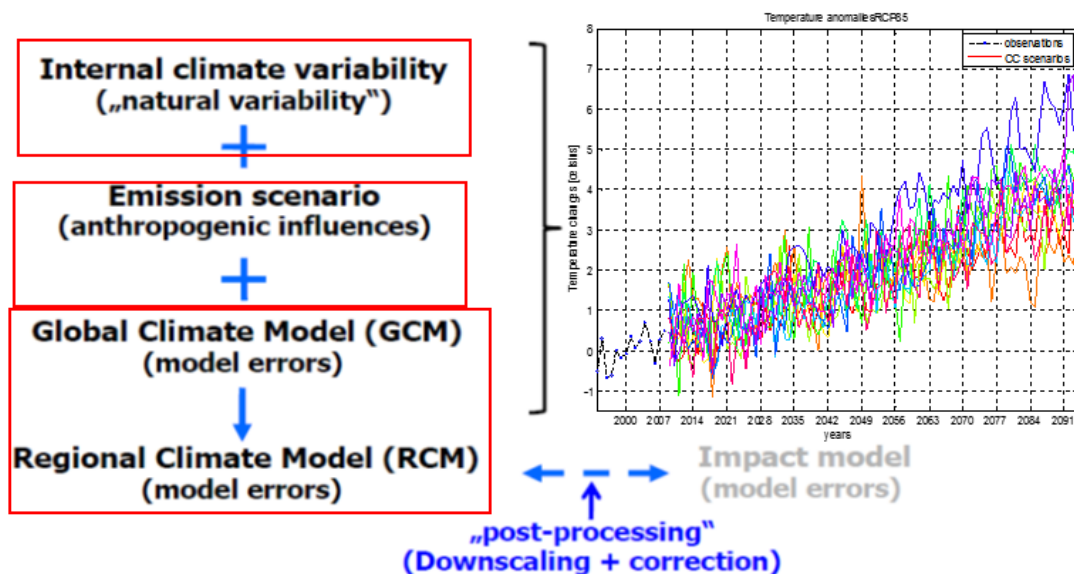


FIGURE 3.21: Sources of Uncertainty in Climate Change Information

Natural variability: Climate can and does vary naturally, regardless of any human influence. Natural climate variability arises as a result of two causes: natural internal forcing and natural external forcing, such as volcanic eruptions and variations in solar activity. Natural internal climate variability is one of the three main

sources of uncertainty in estimating future climate change, and is often addressed by running multiple simulations of climate models.

Future emissions of greenhouse gases (socio-economics): The starting point for projecting future climate change is the development of scenarios of future emissions of the greenhouse gases and other pollutants that affect climate (e.g. sulphur dioxide). Such scenarios extend data on past emissions with estimates of how emissions may change with future changes in technology, demography, economic development, etc. All these factors, and hence future emissions of greenhouse gases, are a source of uncertainty about future climate change. The most comprehensive attempt so far to characterize global emissions is the IPCC Special Report on Emissions Scenarios (SRES). In relation, as an extent of SERES, in our case we deal with most recent initiative or the next generation of scenarios to support climate change research and assessments are called Representative Concentration Pathways. These scenarios prescribe trajectories for the concentration (rather than the emissions) and therefore are not simply updates of the SRES emission scenarios. Unlike SRES in which no mitigation policies are implied, the RCPs cover the full range of stabilization, mitigation and baseline emission scenarios available in the scientific literature. The RCPS provide a consistent set of greenhouse concentration trajectories that are intended to serve as input for climate modelling, pattern scaling and atmospheric chemistry modelling. It should be noted that the consequence of uncertainty in emissions for climate projections is much less for the near future climate (2020s) than for the distant future (2080s). Climate projections based on four of the commonly used SRES scenarios do not start to diverge significantly until just before mid-century. Near-term (next 15-20 years) climate is dominated by historic emissions of greenhouse gases, and natural climate variability. Uncertainty about future emissions, which in turn depend on political decisions as well as uncertain economic and technological development, is an important source of uncertainty in climate projections of more than 50 years. Anyway this uncertainty is quite different of the other uncertainties, since it barely depends of the observations, and historical measurements. For instance there is no exact choice of scenario, thus we have to simulate the entire procedure through the entire horizon. It should be mentioned that similar case stands for the performance indicators, since they should reflect the stakeholder's interests. The district model

is explained above and it can be seen that the farmers are modeled separately as selfish and interested only in the profit. In chapter 2, it is mentioned that there are 66 farmers but not all of them are active, so the MAS does not stand straight forward, so the performance of the indicator carry more uncertainty. Nevertheless the purpose of the indicator performance is not strictly related to the stakeholder's behavior, but more to the influence of the CC scenarios to their profit, or the revenue changes.

Another uncertainty related with the socio-economic development and natural variability is the glaciers dynamics and the complexity of the hydrological models. Therefore our HBV is quite simple and old model that excludes the glacier dynamics, so the results might be still improved if more complex model are developed. Here again we deal with uncertainty over crossing, since we deal with all sources of uncertainty, starting the explanation from socio-economics.

Modelling uncertainty: Uncertainty about the functioning of the climate system, and the responses of biological and social systems to changes in climate, is another source of uncertainty for adaptation planning. Continued scientific research may help to resolve some of this uncertainty but it may also uncover additional uncertainty. Because different climate models represent these processes in different ways, their outcomes (for the same emissions scenarios) will be different. Methods for quantifying the uncertainties that are associated with different climate models have therefore been developed.

One dimension of uncertainty in climate projections that is related to modelling uncertainty arises from downscaling. Regional climate models or statistical downscaling techniques are often used in order to provide climate change information at a scale smaller than that of global models give (typically 300km). Regional climate models can better take account of regional geography and topography (e.g. mountains and oceans), and are therefore better at representing local variations in climate. Statistical downscaling applies statistical relationships between observed small-scale (often station level) variables and larger (global model) scale variables to derive climate projections at a more detailed spatial resolution. It is important to note that both regional climate models and statistical downscaling techniques inherit errors from the global models that drive them. Considering the few different papers like (Hawkins and Sutton, 2009)), (Prein et

al., 2011), (Dequé et al., 2007; 2011), (Hamlet, n.d.) We made a suggestive participation of the uncertainty:

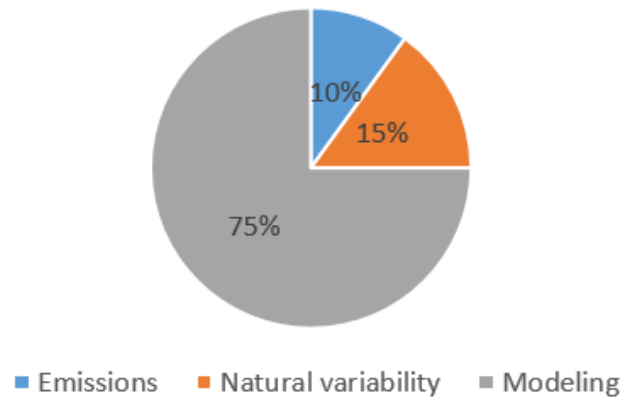


FIGURE 3.22: Partition of the Sources of Uncertainty in CC information

Furthermore, we go on analyzing into deep we can get more comprehensive data about the precipitation and temperature and the percentage of influence by the already defined sources of uncertainty (Prein et al., 2011).

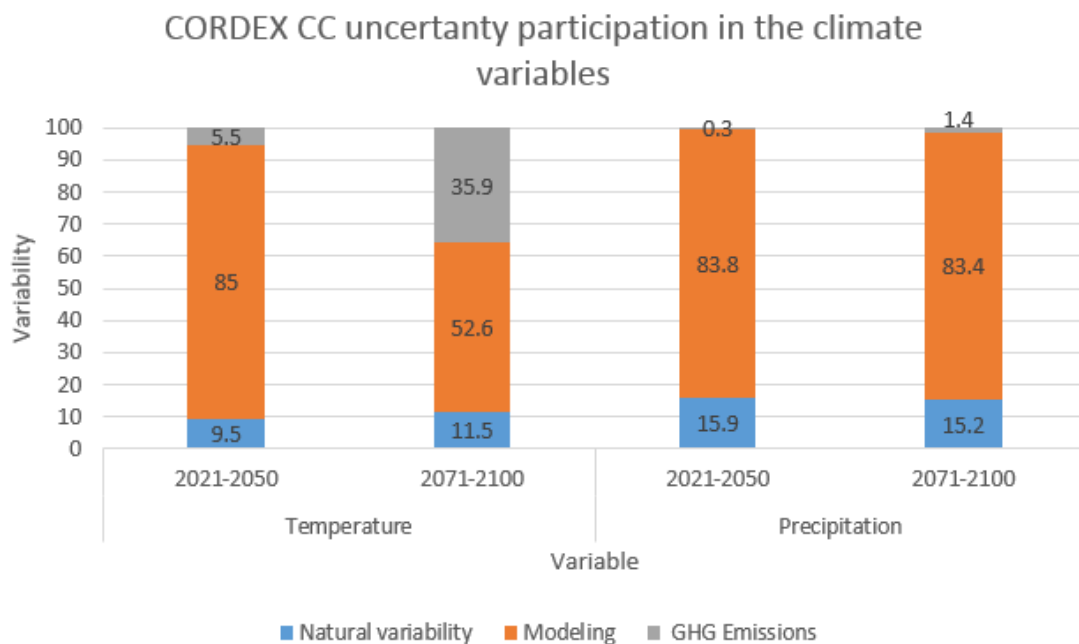


FIGURE 3.23: Partition of the Sources of Uncertainty in CC variables

Therefore following conclusion are made:

- Emissions partly contribute at the end of the century (depends on parameter).
- GCMs contribute the major fraction to uncertainty over Europe (and worldwide).
- Natural variability contributes ; 15% for 30 yr averaging periods (more for shorter periods! (Hawkins and Sutton, 2009)).
- RCM uncertainty is slightly less important than GCM uncertainty (Dequé et al., 2007; 2011).

Furthermore this study has a mission to assess which uncertainty influence at most, hence the experiment setting is following instruction in order to define which uncertainty is influencing the most, considering the statistics, as well as the performance of the indicators. The paper related with the CC impacts (Anghileri et al., 2011), argue that RCM as one related with the local data, mostly influence to the uncertainty.

3.5 Quantifying the uncertainty

Generally the process for water planning relies on estimates of water supplies over time. The overall supply to an entity may encompass supplies from groundwater, stream flow, and other surface water sources. In our case we only have model that that describes or simulate the regulated lake of Como and the discharges in the Como catchment area. The Muzza irrigation district is receiving water from the controls assigned to the dam on Como Lake, through the Muzza channel. The rest is detailed integrated model about the agricultural district of Muzza which includes, 3 modules and feedback route. Depending on the assumptions made about the future state of the water supply sources, there can be multiple sources of uncertainty that may need to be accounted for. It is important to acknowledge upfront that in most cases, it is infeasible to try to quantify all possible sources of uncertainties. The focus should be on the areas of uncertainty which would create the largest impact on the forecasted outcome and/or which typically dominate the other (less significant) uncertainties in the forecast model for water supply. In our case as it was spoken before the greater impact to the entire uncertainty would be focused on the input values depending of the CC future scenarios, and less significant would be the uncertainty caused by the modeling and all other socio-economics factors.

In addition the groundwater resources and the irrigation channel leakage also has to be considered in the future water supply, but in our case this change is taken as constant or not changing in the control period. In fact the sensitivity analysis in this study will

be focused on the CC scenarios and the uncertainty of the model will be left for future research in order to check the parameters set the performance and so on. Anyway one can make a confusion between this uncertainty since we going to deal with the model inputs and outputs, which were considered as model uncertainty , but how ever for the sake of simplicity will call all them CC uncertainty or input/output uncertainty[22].

3.5.1 Quantifying the Uncertainty in climate future scenarios

As it was discussed in the previous sections the uncertainty from the future scenarios depends on three major source:

- Natural variability
- Emissions or in our case RCPS
- Model properties accompanied by the dynamical downscaling for RCMs and statistical downscaling for our local purposes.

The GCM/RCM should be chosen so that they represent the best knowledge about pertinent climate trends while adequately representing the variability in the predictions of interest (such as precipitation and temperatures)[23]. Next, multiple "emission futures" need to be selected (already chosen RCPS) to feed the Lake/District models. These emission futures depend on assumptions of how society, at large, will respond to climate change .

Multiple emission futures (RCPs) combined with different multiple GCM/RCMS come up with an ensemble of "climate scenarios" that can be assumed to represent the uncertainty in future climate conditions. Note that the more "climate scenarios" that are used, the better the characterization of uncertainty will be. Thus, it is recommended that all available information be utilized in coming up with these climate scenarios. It is possible to ascribe likelihoods to each of the climate models typically by assuming that climate scenarios that show large discrepancies with existing data may be deemed less likely than those that are most consistent. However, it is not recommended to assign quantitative likelihoods without strong scientific justification as this may lead to biased results. It is preferable (and more conservative, from a decision-making perspective) that each model and scenario be treated as equally plausible and be given equal

likelihood – this is the approach followed in this study. Furthermore, as it has been said there are around 50 combination of models RCPs/GCM(RCM) and all of these are downscaled for our scale. The ones downscaled for Como catchment area are used to run the HBV-rainfall/runoff model in order to estimate the discharges in Como Lake. The other ones are used for the Irrigation district model in order to calculate the yield and the needs for future water supply and to run the possible crop rotation. The outputs of these models are summarized in indicators used in order to solve the optimization problem solved using SDP. The Pareto frontier is formed for the optimal solution that is commented in details, later on. The data-set of downscaled predictions for temperature and precipitation changes for multiple models and different carbon emission scenarios can be assumed to encapsulate the uncertainty in future climate conditions. Analysts will need to select scenarios for their region of interest. Typically, it is computationally unfeasible to select all 50 scenarios. However, a subset of these scenarios can probably be chosen such that they bound the variability in temperature and precipitation predictions while realistically representing the potential for economic and social growth for the region of interest.

3.5.2 Quantifying the uncertainty in the models

Water supply projections typically rely on numerical models that predict water supply for given sets of management, climatic, and hydrologic conditions. Surface water and groundwater models have both shared and distinct sources of uncertainty. The key to incorporating uncertainty in water supply models into the regional planning process is to first identify the source of uncertainty and then to define a range of inputs/parameters or different models (with different reasonable modeling assumptions) that result in multiple estimates of water supply[21].

If the conceptual model (consisting of underlying assumptions and approximations) is thought to be uncertain, multiple models with a range of plausible conceptual assumptions may be used – for example, rainfall/runoff models with varying hydrologic boundary conditions. The water availability predictions would then be made for this ensemble of models.

The uncertainty in model inputs and parameters can often be reduced by using external data to constrain the range of the values that these may take. The process of model

calibration is essentially a means to reduce uncertainty in model parameters by matching model predictions with known data about the behavior of the modeled system. For example, the evaporation and discharges values used in HBV can be "calibrated" by matching measured inflows with those that the model predicts.

Uncertainty in model inputs and parameters can also be reduced by using direct information about these inputs and parameters. This process is often referred to as "conditioning" inputs and parameters to data. For example, available literature values of used crops for a certain climate might be used in the model in order to run the required rotation.

While uncertainty in inputs and parameters may be reduced by the above measures, *it cannot be completely eliminated*. For example, there still remains some uncertainty in calibrated models due to insensitive input/parameters and errors in field observations.

The produced different layers of uncertainty may be combined by using a nested approach – multiple conceptual models run with multiple inputs/parameters. Obviously, such an approach imposes a significant computational burden and may not be feasible in many cases. In such cases, it is recommended that only the more significant sources of uncertainty be characterized.

Chapter 4

NUMERICAL RESULTS

4.1 Experiment setup

This section introduces the reader to the setup used in the experiment running. The important and unique aspects of the experiment are described. The procedure on generation and characterization of the models is described in the previous chapter or there are suggestion for a related literature. The subsections are related with experiments developed within the thesis work, or with some important step decisions or assumptions.

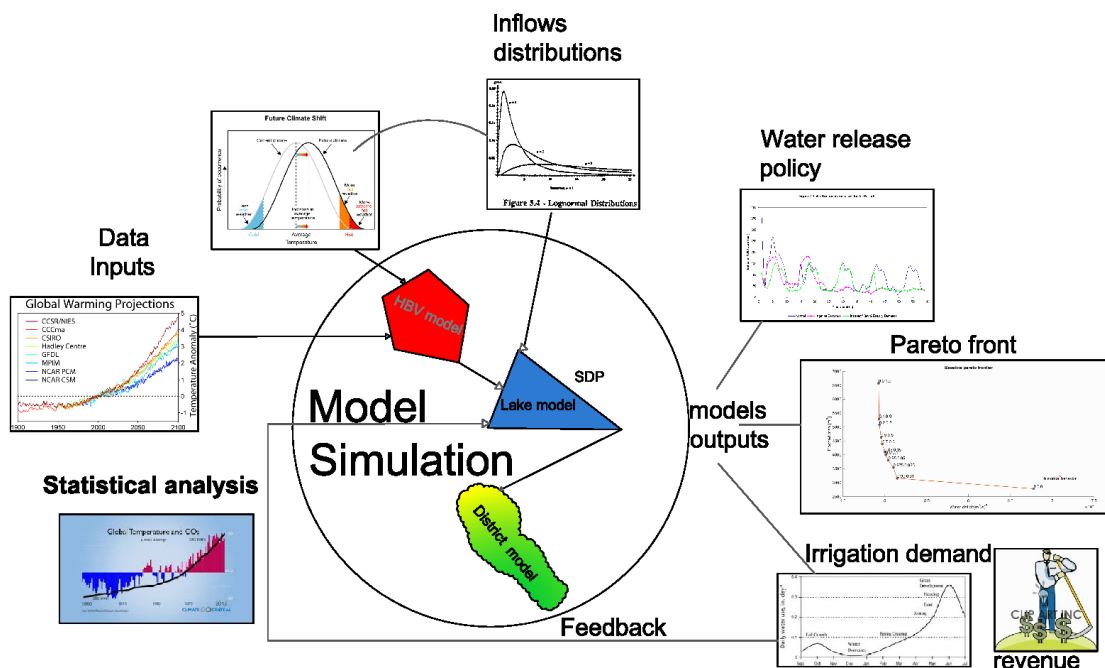


FIGURE 4.1: Modeling simulation scheme

4.1.1 Scenarios setup

As it was anticipated in Chapter 2 the first step of the procedure is discovering analyzing the future scenarios from EUROCORDEX framework. Therefore, detailed exploring of each GCM/RCM combination was done. Since this framework is quite new, not all the scenarios were available with high resolution EU-11 (0.11 degrees or 12.5km). For the ones that EU 11 was not available we kept on with the lower resolution, EU 44 (0.44 degrees, 50km). From table 4.1 it can be seen that not all the combinations were available on the server (red fields) and not all were consistent resolution correspondence (yellow fields).

TABLE 4.1: CC models combinations and directions of the experiment, EUROCORDEX framework

temperature (tas)							precipitation(pr)						
	CCLM4-8-17	HIRAMS	RACMO22E	RCA4	REMO2009	WRF331F		CCLM4-8-17	HIRAMS	RACMO22E	RCA4	REMO2009	WRF331F
<i>rcp 26</i>							<i>rcp 26</i>						
CCCma-CanESM2							CCCma-CanESM2						
CNRM-CERFACS-CNRM-CM5							CNRM-CERFACS-CNRM-CM5						
ICHEC-EC-EARTH				11, 44			ICHEC-EC-EARTH				11, 44		
IPSL-IPSL-CM5A-MR							IPSL-IPSL-CM5A-MR						
MIROC-MIROC5							MIROC-MIROC5						
MOHC-HadGEM2-ES							MOHC-HadGEM2-ES						
MPI-M-MPI-ESM-LR							MPI-M-MPI-ESM-LR						
NCC-NorESM1-M							NCC-NorESM1-M						
NOAA-GFDL-GFDL-ESM2M							NOAA-GFDL-GFDL-ESM2M						
<i>rcp 45</i>							<i>rcp 45</i>						
CCCma-CanESM2					44		CCCma-CanESM2				44		
CNRM-CERFACS-CNRM-CM5		11			11, 44		CNRM-CERFACS-CNRM-CM5		11		11, 44		
ICHEC-EC-EARTH		11	11, 44	11, 44	11, 44		ICHEC-EC-EARTH		11	11, 44	11, 44	11, 44	
IPSL-IPSL-CM5A-MR					44	11, 44	IPSL-IPSL-CM5A-MR				44		11, 44
MIROC-MIROC5					44		MIROC-MIROC5				44		
MOHC-HadGEM2-ES					11, 44		MOHC-HadGEM2-ES				11, 44		
MPI-M-MPI-ESM-LR		11, 44			44	11	MPI-M-MPI-ESM-LR		11, 44		44	11	
NCC-NorESM1-M					44		NCC-NorESM1-M				44		
NOAA-GFDL-GFDL-ESM2M					44		NOAA-GFDL-GFDL-ESM2M				44		
<i>rcp 85</i>							<i>rcp 85</i>						
CCCma-CanESM2					44		CCCma-CanESM2				44		
CNRM-CERFACS-CNRM-CM5		11			11, 44		CNRM-CERFACS-CNRM-CM5		11		11, 44		
ICHEC-EC-EARTH		11	11, 44	11, 44	11, 44		ICHEC-EC-EARTH		11	11, 44	11, 44	11, 44	
IPSL-IPSL-CM5A-MR					11, 44	44	IPSL-IPSL-CM5A-MR				11, 44		44
MIROC-MIROC5					44		MIROC-MIROC5				44		
MOHC-HadGEM2-ES					11, 44		MOHC-HadGEM2-ES				11, 44		
MPI-M-MPI-ESM-LR		11, 44			11, 44	11	MPI-M-MPI-ESM-LR		11, 44		11, 44	11	
NCC-NorESM1-M					44		NCC-NorESM1-M				44		
NOAA-GFDL-GFDL-ESM2M					44		NOAA-GFDL-GFDL-ESM2M				44		
<i>historical</i>							<i>historical</i>						
CCCma-CanESM2					44		CCCma-CanESM2				44		
CNRM-CERFACS-CNRM-CM5		11			11, 44		CNRM-CERFACS-CNRM-CM5		11		11, 44		
ICHEC-EC-EARTH		11	11, 44	11, 44	11, 44		ICHEC-EC-EARTH		11	11, 44	11, 44	11, 44	
IPSL-IPSL-CM5A-MR					11, 44	11, 44	IPSL-IPSL-CM5A-MR				11, 44		11, 44
MIROC-MIROC5					44		MIROC-MIROC5				44		
MOHC-HadGEM2-ES					11, 44		MOHC-HadGEM2-ES				11, 44		
MPI-M-MPI-ESM-LR		11, 44			11, 44	11	MPI-M-MPI-ESM-LR		11, 44		11, 44	11	
NCC-NorESM1-M					44		NCC-NorESM1-M				44		
NOAA-GFDL-GFDL-ESM2M					44		NOAA-GFDL-GFDL-ESM2M				44		

4.1.2 Downscaling

After choosing the available scenarios, the downscaling was performed in MatLab, visualized in ArcGIS in order to validate the results and to calculate the areal precipitation. The areal precipitation is calculated using thissen method or in other words, we determine the effective uniform depth of precipitation over the basin (essentially the average precipitation). The procedure of downscaling goes in 2 parts, calibration and application. For calibration of the QQ mapping method we used the observation from 1965 to 1980 and the historical or backcast). Same downscaling procedure was performed separately for Muzza district and Como Catchment. Como catchment assumed areal precipitation, Muzza downscaling was performed using the meteo stations data for the precipitation.

4.1.3 HBV discharges production

The HBV model and its mechanism was explained in Chapter 23, runoff generation was only performed for Como catchment, which was used as an inflow to Como lake in order to proceed the lake modeling and the optimization. Therefore the inflows produced from the scenarios are inputs in the Bellman function used for the SDP (check App.A) and in the lake model. Before nesting the inflows as a model inputs, we have to deal with some problems and assumptions anticipated before. For instance we need the inflows as inputs of the lake model and we need derived parameters of the inflow data for the stochastic description in the optimization procedure (SDPs, A). The first is quite straight forward, and it assume only converting into m^3/s , from mm/d . The later might cause trouble, since the chosen distribution is lognormal, and we have zeros in the data samples (check Ch.3, section..). Now either we change the probability distribution, since $\log 0 = -\infty$, or we do some assumption. We decided to do a simple assumption by adding $0.01 m^3/s$ to each inflow data, having in mind that the HBV inflows already underestimate the real ones. With this deed we deal with the zero inflows and we do not influence the global mean and standard deviation, in a sense that adding negligibly small number will lead to different parameters and improper fitting curve. However fitting the data is beyond the scope of this study and it is commented in some other studies like books for Statistical Methods in water resources management by D.R. Helsel and R.M. Hirsch.

4.1.4 District Model Inputs

This model is mostly based on empirical formulas, thus it requires lot of input parameters. Most of the parameters were left as they were defined from Mateo Mainardi, and than updated several times by people working on this model. Most important groups of parameters are:

- Crop-related data that are included in the database of the software IDRAGRA for each crop of interest
- The required **meteorological inputs** are the time series of the average daily rainfall, maximum and minimum temperature, wind speed, maximum and minimum relative humidity and solar radiation. These are the most important for this study. Even-though it is suggested to include as much as possible data, related with the farmer's units. In this analysis, for the new modified model we only include one station and the meteorological data related with that one. The station is San Angelo and it located on the south-west of the Muzza agricultural district. For the baseline it is straight forward using the existing historical data form 1999-2007. In fact there was limitation in the data availability, so the last updates were not available. Otherwise, we consider three meteo stations, which are considered in the downscaling procedure, and that data is spatially distributed, using inverse distance weighting method.

The CC data is nested in the same matrices. One can notice that we only talk about two future projected climate variables, precipitation and temperature. The rest of the parameters remain the same. This is one of the assumptions and limitations of this study.

- **The irrigation-related data** are the time series of the average daily flow diverted by the water sources. The flow input is taken from the lake model simulation, according the the feedback demand of the farmers and available inflow at the current step. The water released form the lake dam is diverted to all the districts, that are supplied by Adda irrigation system, each of them share the daily outflow. For Muzza region we also we 66 units which require different amount of water. Therefore the partitioning correspond to the daily demand of each unit , and it is delivered like that.

- Finally series of **soil-dependent parameters**, are entered, mostly related with the conductivity of the soil.

4.1.5 Experiment setup

The experiment design is critical to correctly understand the system's behavior. For this reason, three different kinds of settings are adopted with its specific purpose, as explained below:

Experiment 1: If we want to measure and compare the performance of the system in future first we need to look into the *baseline performance*. In the Baseline we deal with a deterministic normative water demand assigned a priori by an expert and it does not differ during the time, it follows the same trajectories over simulation horizon. The demand is constant and also the land use is as it is on the field, business as usual. Also the same policy of CAP is assumed in order to maximize the profit of the farmers. However the optimization is dedicated only to control states of the lake, or the releases of the regulator for a constant demand, but different inflows. Here we consider only one weight combination or the one mostly related with the historical point and experts suggestions $w_{irr}=0.025$ and $w_{flood}= 0.975$. Anyhow this experiment is associated with Ch.2, where the baseline performance of the system is described, mainly describing the historical behaviour of the Lake manager. Later in section 4.3, we offer a comprehensive comparison between so called *normative deterministic optimization* and *adaptive deterministic re-optimization*. One can easily figure out that the first is considering constant normative demand, maybe periodically changed, and the second one is considering the farmers feedback.

Experiment 2: The second part is related with uncertainty exploration for the baseline simulation. The difference here is that we have the feedback from the farmers. The water demand is updated each year through the horizon, and then the lake manager is re-optimizing the release policy based on the updated demand. In order to explore the uncertainty we have defined the few combinations of weights to construct the Pareto front. Moreover, few more uncertainties are explored, such as intrinsic uncertainty related with the natural variability and choosing the simulation horizon.

Experiment 3: The next experiment is dedicated to the CC scenarios, and understand the contribution of uncertainty from GCM, RCM and RCP separately. (presented with arrows in table.4.1)Therefore we define the following simple guidelines for exploring and discussing this experiment :

GCM uncertainty exploration: Follow the shadowed column in the fig4.1 And explore the uncertainty related only to one RCM and 9 GCM. In same time we over-cross with different RCPs and different spatial resolution. So we gain a knowledge about the uncertainty produced due to the intensity of carbon emission. In other words we have to run the model simulations for all this scenarios. In order to make it consistent with the historical behavior and the re-optimization of the baseline, at the beginning we discuss only one weight combination, which sufficient for quantifying the modeling structural uncertainty as it is described in section 4.5. Later we will extend the experiment running different weight combination,showing the projected trade off.

RCM uncertainty exploration : Follow the shadowed rows in the fig?? and explore the uncertainty produced by different RCMs. For the sake of consistency we will run only the most abundant rows, as the one suggested, so the results would be comparable (one GCM). In same manner we cross over with the RCPs and resolutions. The same framework stands for this experiment,except the working directions.

Although it is common practice to explore the potential adaptive measures in climate change scenarios to mitigate its negative affect, the purpose of this study is to understand the influence of the CC towards the agriculture and describe the system's behavior, so at current stage no mitigation planning action is considered (figure 4.2). Later on, few suggestions will be launched in order to give us a thought how much those planning actions, i.e. Crop rotation, influence the farmers profit.In reference brief trade off simulation is done for the baseline in section4.4.However, the focus of this experiment is to generate results without co adaptation(see appendix C), thus the final conclusion will be dedicated on commenting the robust influence of the CC on the farmers performance and the Lake regulation practices.

Experiment 4: As it was aforementioned the last part of this thesis experiment will be focusing on

a brief exploring of the co adaptation planning action related with crop rotation. This session is only done to see the difference of using co adaptive strategies. Logically this section follows the second experiment and supports it offering even better opportunity for optimizing the system. The experiment will be done only for the baseline horizon, only for comparison, using the optimal or the expert suggested trade off, out of the historical normative optimization. The final outcomes will be represented with raster maps, plotting the crop land use. Generally after each season the farmers choose different crops according the water release and yield from the previous year in order to gain higher profit (for more details check AppendixC and chapter 2).

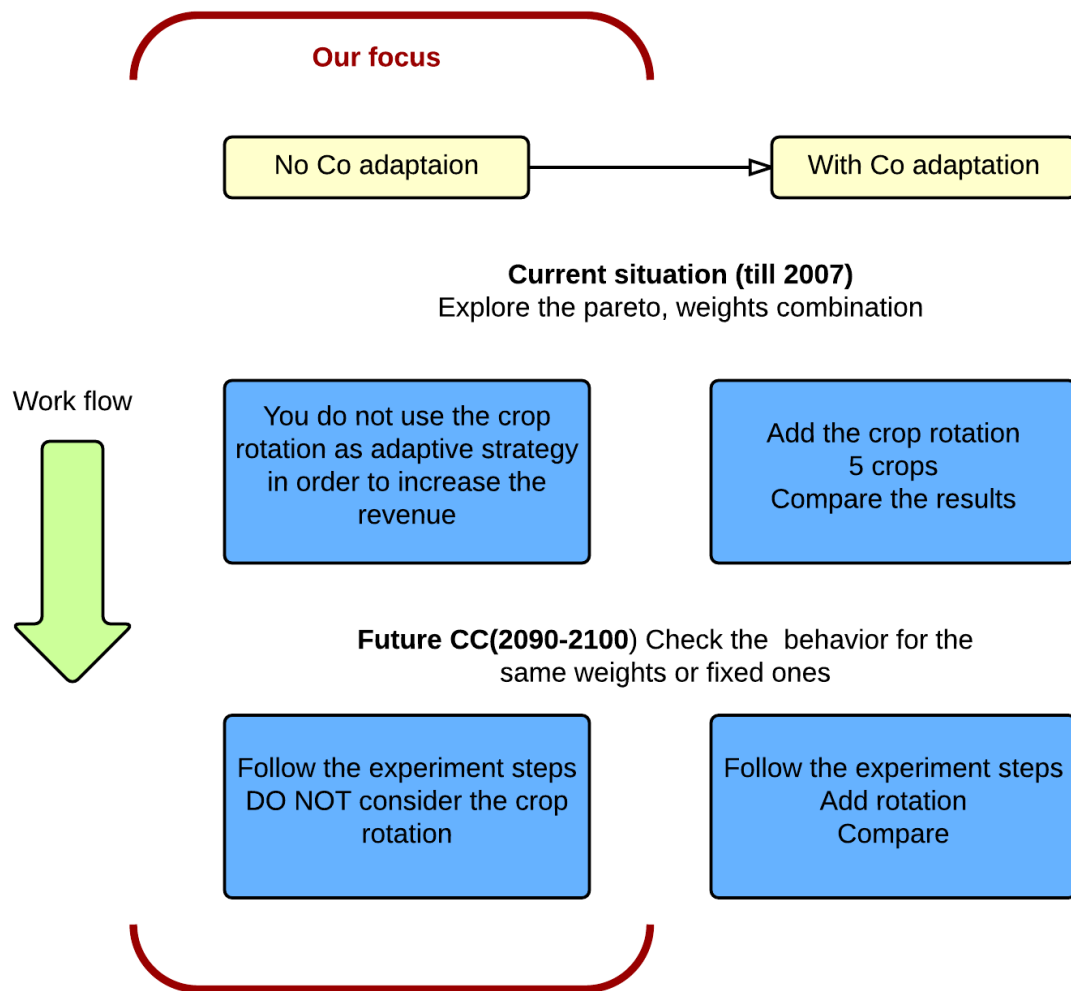


FIGURE 4.2: Framework block diagram

4.1.6 Choosing the simulation horizon

The selection of the horizon firstly, is related with the available data form the historical observations and secondly the circumstances of the environment. In like manner. And third and most important is the new policy adoption about the MEF, that has to be preserved along Adda river, and it takes place from 1999. By the same token, there are changes in the water release policy after 1999.

It was mentioned before that we are going to deal with one year horizon, but the simulation will take place 1999-2007 as a baseline horizon, and for the projected scenarios we are going to consider the last 10 years of the century, as a simulation horizon. The point is to have consistent and comparable horizons that will decently represent the future and current situation. Therefore the future simulation, will be dedicated for the last 10 years of the century as a compensation among the most representative period. However the choice of the horizon is not the optimal one since not for all scenarios the last century years are presenting the worst condition. The drawback of using short horizons, suggested in the literature, is the possibility of not unrealistic representation of the characteristics of the certain scenario or the considered area. This issue will be postponed for later comments during the experiment. Whatsoever, if we consider the straight temperature inclination through the years, we definitely taking the hottest years out of the available CC scenarios horizons. Last reason of considering relatively short horizon is that the computing time of entire model simulation is relatively long, around 30 min per year of simulation for a considered weight combination without taking into account the data processing, making the entire procedure extremely exhausting if you consider 30 CC scenarios trades off.

4.1.7 Assumptions due to the CC scenarios running

Although different assumptions regarding the entire modeling procedure are indirectly mentioned trough Chapter3, here we are going to give a very short overview to the assumption that are done, mostly of practical reasons and because of lack of data. Firstly, as we are using the Lake Model and different coefficient for flooded area estimation, the lake level and the lake state are a necessary input for this calculation. Indeed, we consider the last 10 years of the century, thus calculating the states and the lake levels it is quite exhausting and highly uncertain. One can also freely say that it is imprecise

and not accurate since we only have the precipitation and temperature as future meteo inputs. Therefore we assume that the lake level is the same as the last data available from the baseline simulation horizon, or 2007. The same stands for the lake state or the lake volume included in the lake model regulation. Intuitively the discretized lake state is also the same as the baseline, as well as the initial area and volume of the lake, which in reality would change in future due to different factors. Another assumptions related with the lake model are that all the parameters are calibrated using historical data from 1946-2011, which is also not the best approach when simulating scenarios 100 years later. Other assumptions stand for the meteo inputs in the Muzza region, where the radiation and the wind data are remaining the same as the baseline simulation horizon, hence we do not have any available data, neither a model that can estimate them. Here we can also mention the main assumptions made in the district model, regarding the water prices, crop market prices, the land use and the crop cultivation which are considered same as in 2007.

4.1.8 Numerical results representation

After generating the set of results, the focus is on presenting the optimal solutions generated from the SDP, therefore producing representative Pareto fronts. Since we are dealing with 2D multi-objective space the presentation is quite straight forward. Moreover the indicators values are presented in different ways. For a better perception of the reader or the DM we offer the following representation of the performance indicators: i.) Sum of the mean annual values; ii.) Mean of the annual sum indicators values,iii.) the mean indicators values, over the baseline horizon (1999-2007). In relation they are presented in their original units, making more intuitive for the DMs. The suggested different presentation of the same results is given for better understanding of the indicators values. The approach of presenting the Pareto frontiers might be different in a sense that indicators have different units and values with different order of magnitude. This one can decide to use typical normalization and present the values in range, i.e. 0 to 1. However, here we are going to use the real values of the indicators and present them with adapting the axis limits. Later on the normalization will be presented in order to comment the real influence of the weights in the weighting method (see section4.3 ,chapter3).

4.2 Statistical analysis of the CC(Climate Change) scenarios

Dealing with almost 50 combinations of different precipitation (pr) and surface temperature (ts) combinations of scenarios is quite exhaustive and time consuming procedure, especially if you consider the timing for running the model, explained in the first chapter. In order to handle them in easier way, some subsets of scenarios have to be chosen. In addition each scenario has different driving model or different RCM which prevails unique performance. In order to define their behavior, to locate future trends induced by the models, locating extreme events e.g. dry, wet years) we perform the following statistics. This section is dedicated for giving a general picture of the future climate behavior, the mentioned subset of the scenarios that will be used for running the models and exploring the uncertainty is given in the previous section, where the set of scenarios is done in order to quantify the uncertainty coming from different sources. However here we will offer a nutshell of future CC and a comparison with the baseline climate. Before we start presenting the results it is worthy to be mentioned that most of the statistics is done in the period of April to September, thus we will denote this period as "*irrigation period*".

4.2.1 Raster plots in the irrigation period

Precipitation For the purposes of analyzing the precipitation predicated and down-scaled regarding different combinations of GCM/RCM/RCP, we make the comparison taking the annual sum of precipitation in the period of 1st of April until 1st of September, or the irrigation period. The following graph give us information, scaling from blue to red as wet to dry years. There are two graphs related to two different pathways RCP45 and RCP85. Mark out that the scenario associated with RCP26 is added to the ones of RCP45, even though entirely different concept of emission distribution is assumed .

$$P = \sum_{i=1}^H pr_i \quad (4.1)$$

RCP45

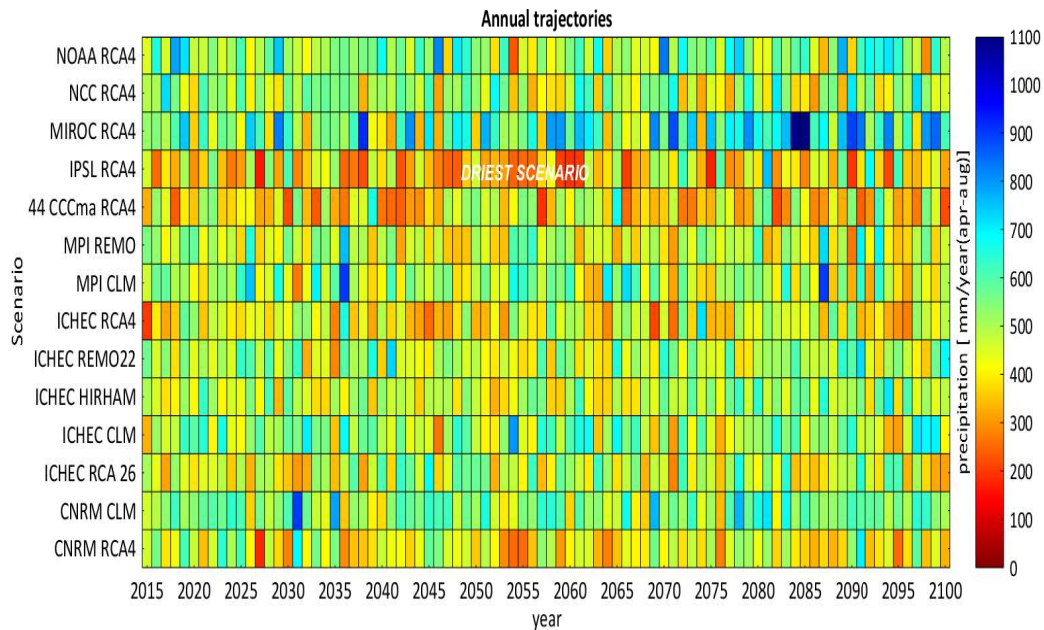


FIGURE 4.3: Raster representation of the annual Precipitation trough the century, RCP45

Note: In fig.4.3 the first name of the model is related with the first abbreviation of the related GCM, the second with the RCMs. The model with 26 refers to RCP26. After the number 44 moving upwards the resolution switch from EU 11 to EU 44. The same stands for the rest of the figures

At first, in fig.4.3 it can be noticed that with changing the resolution from EU 11 to EU 44, pr shows different behavior of the models. As it is expected EU 11 reliable information, in sense closer than the observations, therefore no extreme years are shown. EU 44 scenarios like CCC and IPSL are showing very dry years with pr lower than 300mm, but MIROC and NCC perform wet years performing rainfall higher than 600 mm. The mentioned scenarios are EU 44 resolution. From the EU 11 resolution the presented combinations do not differ that much one to each other. The scenario CNRM CIM can be separated as the wet one, even showing less prr than the EU 44. The scenarios associated with the RCM named RCA4(developed at Rossby Centar), perform hotter years than the rest(e.g ICHEC and

MPI). Also in EU 11 here and there might be noticed extreme years like super dry $pr > 150$ mm, and super wet $pr > 900$ mm.

RCP85

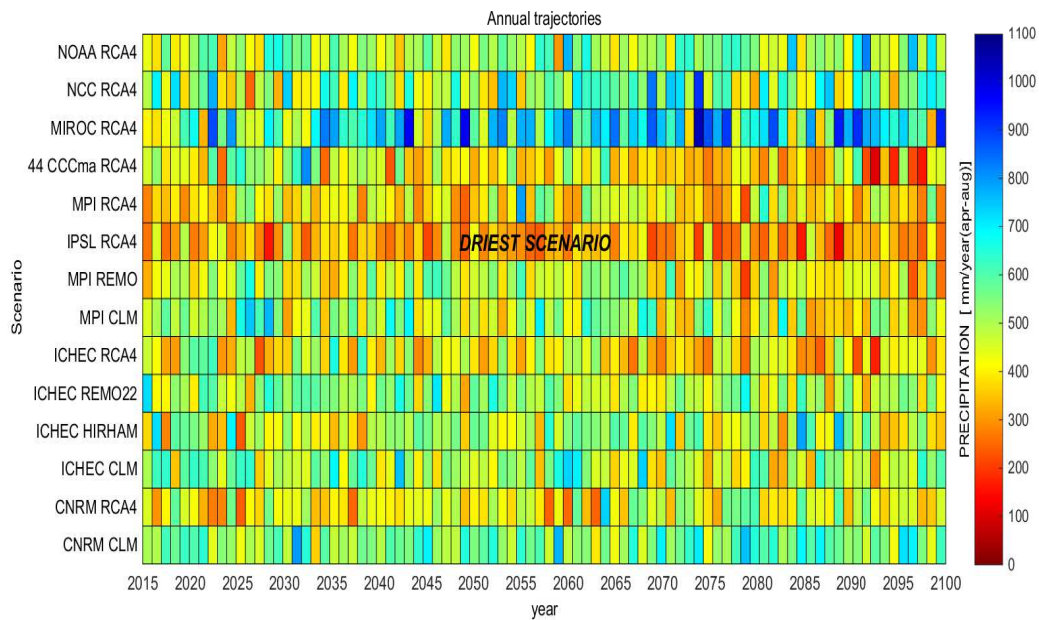


FIGURE 4.4: Raster representation of the annual Precipitation through the century, RCP85

The results in fig.4.4 show that the behavior differs much from the ones of RCP45. In general RCP85 shows lower intensity, which is in fact expected since RCP85 gives more intense emission trajectories as well as more intense socio-economical behavior. Therefore MIROC definitely presents the most wet scenario and IPSL the driest years in the set. EU 11 are also behaving very similar, except taking into account that IPSL is EU11 for RCP85. Therefore again the scenarios associated to RCM RCA4 perform the driest years and CRNM CCLm, ICHEC REMO and ICHEC HIRHAM are showing wet performance.

Cumulative Distribution Function (CDF), RCP45

The next statistics performed is called empirical cumulative distribution function obtained from the data of the scenarios. As it is known in probability theory and statistics, the cumulative distribution function (CDF), or just distribution function, describes the probability that a real-valued variable x_{scen} (in our case

the data array from a regarding scenario) with a given probability distribution will be found to have a value less than or equal to $x_s cen$ (check section ??).

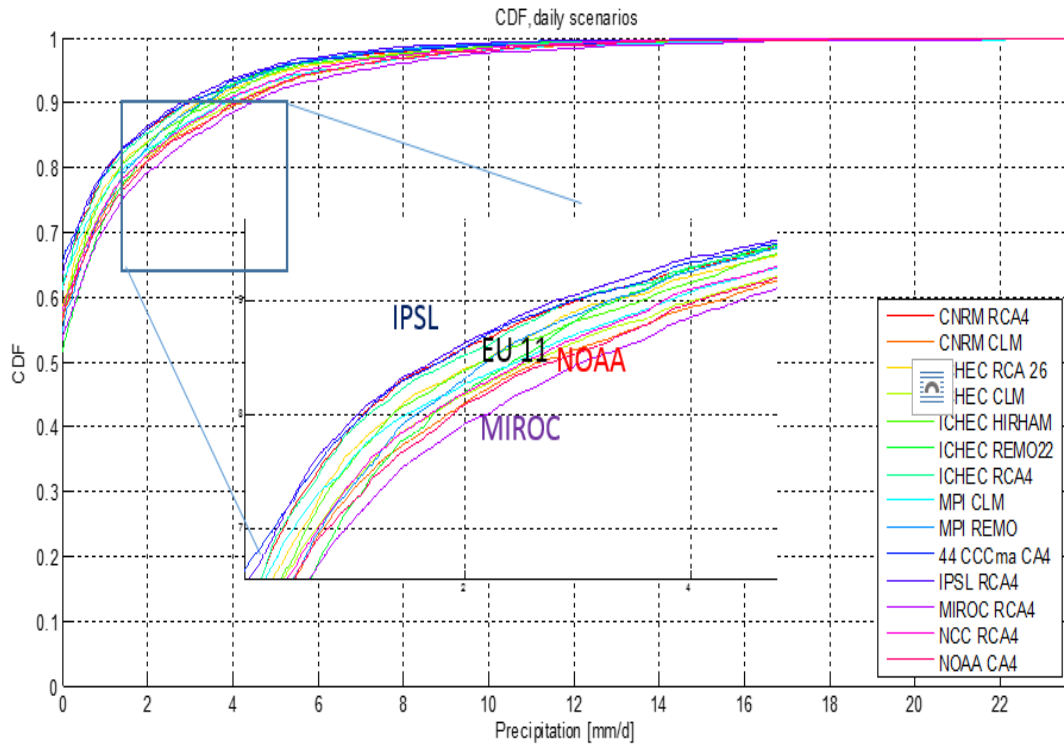


FIGURE 4.5: Cumulative Distribution of the annual Precipitation trough the century, RCP45

First thing that is seen in fig.4.5 is that more than 50% of the precipitation events in the period of April until September are without rainfall or with rainfall close to zero. The available distributions presents us that the precipitations between 0 and 4 mm/day are prevailing in the entire horizon with highest probability of happening. More than 90% of the rainfall events show probability less than 4 mm. As expected MIROC give us highest probability of precipitation above 4 mm/d, and IPSL the lowest. In the middle, between these two extreme scenarios we have all EU 11 varying starting with CRNM CLM as the scenario with wettest years ending with CNRM RCA4 as the one with driest. Here in fact it can be noticed the added value from the dynamical downscaling.

Cumulative Distribution Function (CDF),RCP85

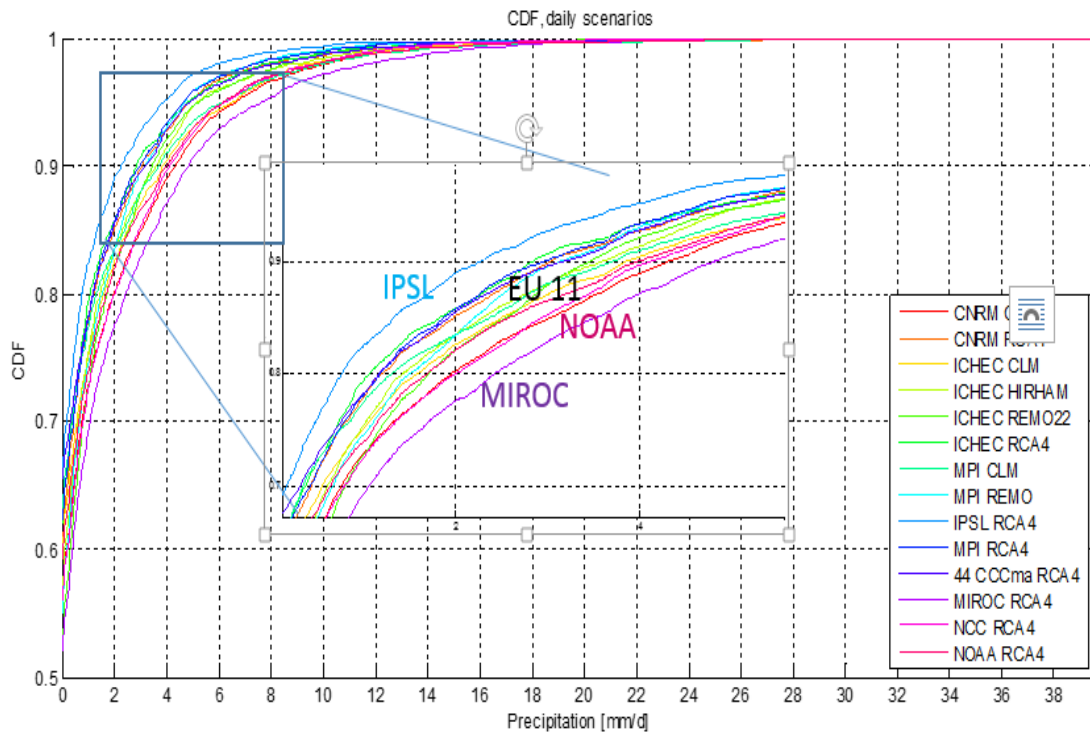


FIGURE 4.6: Cumulative Distribution of the annual Precipitation trough the century, RCP85

Again the cumulative distribution in fig.4.6 is similar comparing the different emission scenarios. IPSL here is behaving even stranger giving us even drier events, but that follows the different resolution since here IPSL is EU 11. Another important remark is that here the distributions are noticeably steeper, that is regarding the more intense concentration pathways. In other words we can say that there are more dry events instead.

Temperature The statistics performed for the temperature variables obtained from the RCMs models consists of taking the mean temperature for the period of April - September for each year, as well as defining the standard deviation of the same sequences. This statistics is performed in order to check the hottest scenarios, as well as the scenarios that shows the highest deviation regarding the mean temperature in the control period. It has to be noted that assuming mean temperature in the irrigation period, we can only assess the CC influence towards plants and crops. While the inflows generations, the

eventual temperature influence on the evapotranspiration of the lake surface, or the snow melting, cannot be commented having the mean temperature as a proxy.

$$T_{mean} = \frac{1}{H_{apr-sep}} \sum_{i=1}^{H_{apr-sep}} t_i \quad (4.2a)$$

$$T_{std} = \sqrt{\frac{1}{H_{apr-sep}} \sum_{i=1}^{H_{apr-sep}} (t_i - t_{mean})^2} \quad (4.2b)$$

RCP45, Temperature mean

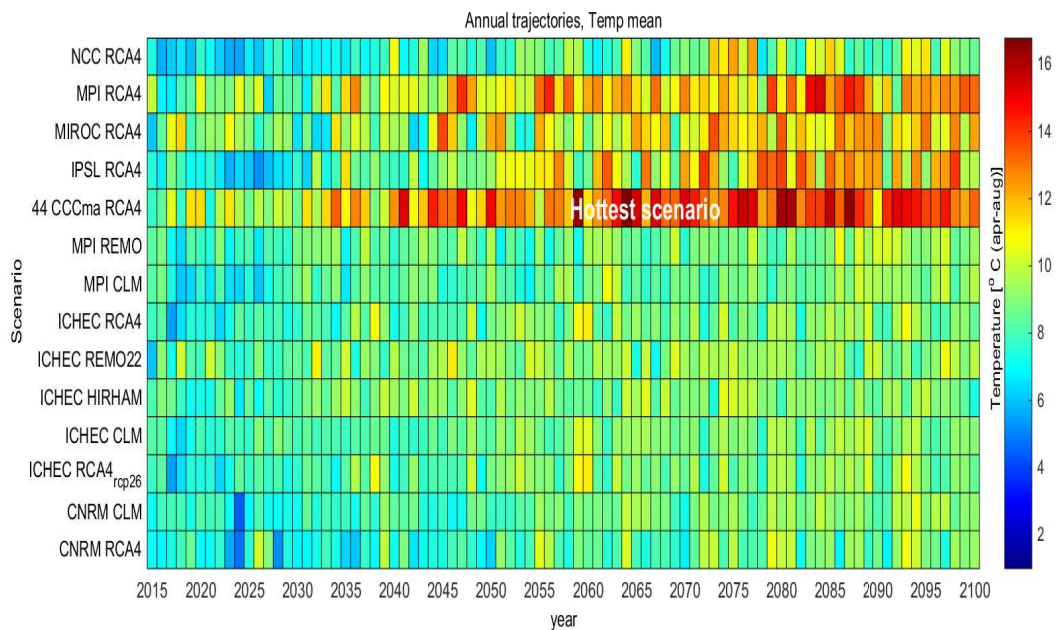


FIGURE 4.7: Mean annual temperature RCP45

From the graph 4.7 we cannot learn about the trends of the temperature in the future, but it is noticeable for some scenarios that during the horizon we get hotter and hotter years. In general EU 44 scenarios perform hotter years with visible trend of increasing through the years. The hottest performance is given by CCC than followed by all EU44. The resolution 0.11 give us very similar temperature for all the scenarios, beside the fact of different distribution of the hot or cold years. In fact the do not differ much of the observation used for downscaling procedure,

explained above.

Standard Deviation of the temperature

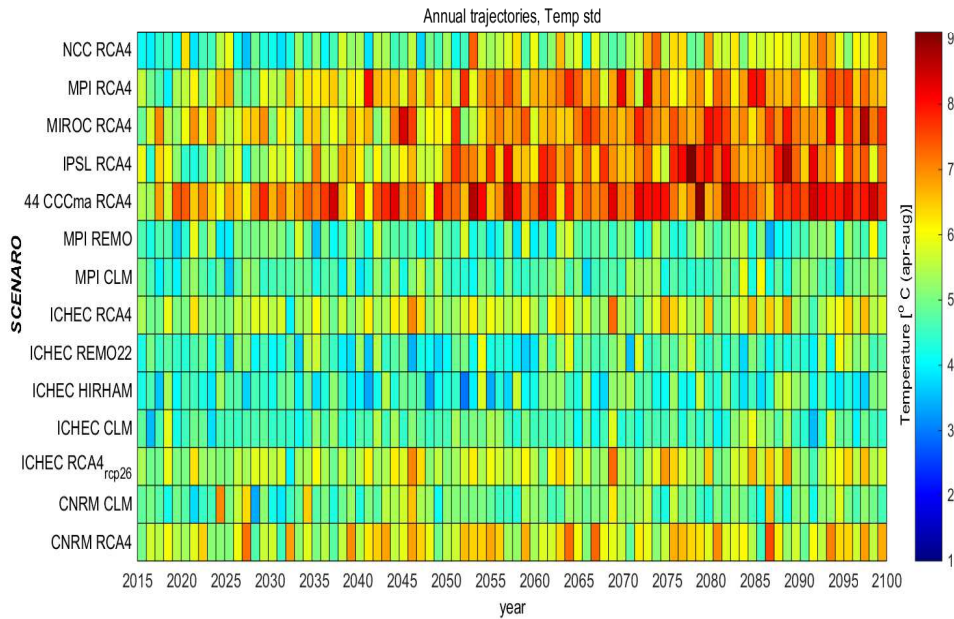


FIGURE 4.8: STD of the annual temperature RCP45, regarding the irrigation period

The standard deviation provide us an information related to the deviation of the temperature around the mean. As expected the most “deviant” behavior is related with EU 44 resolution. CCC is most emphasized giving annual values higher than 7 Celsius degrees variation around the mean. The scenarios with higher resolution do not differ much. Definitely, we should separate the scenarios related to the RCA4, their STD is highlighted the most. One scenario that is not peer to these RCPs, but because of no data availability was added here, IHEC with radiative force 26 W/m² also perform high STD. In relation the STD give us weak knowledge about the range of the temperature variation during the representative period.

Mean Temperature for RCP85

The future temperature trajectories generally show one trend of behavior and depending of the circulation model they only differ in the magnitude of increasing the temperature trough the years. The behavior again is very similar to the 45 W/m² pathway, except the higher temperatures. Here CCC give values of 22 degrees average in the end of the century .Also the increasing of the mean trough

the horizon is more visible also for EU11 in comparison with RCP45 where we could not see any noticeable trend.

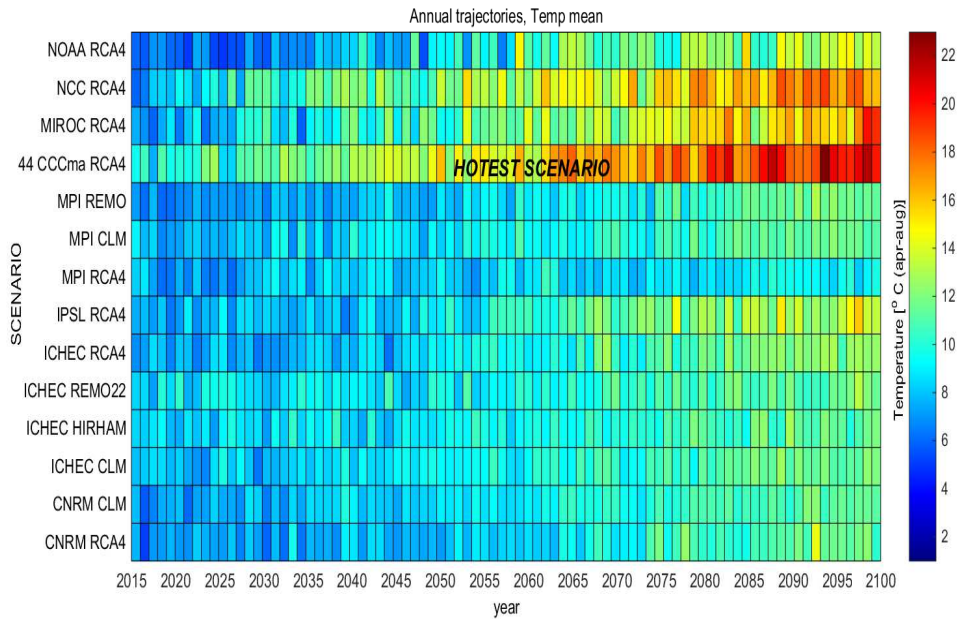


FIGURE 4.9: Mean annual temperature RCP85

STD of the annual temperature for RCP85

Recalling the graph of the RCP45(fig.4.8) the change is insignificant the STD is almost the same, despite the values, naturally here shows higher values of deviation due to the higher radiative force of the pathway. Again to remark the resolution change of IPSL scenarios. This behavior similarity is result of the dependence of the circulation models characteristics. Obviously they are developed in the same way despite the input emissions, in that sense they project similar deviation, despite the RCPs, the higher value of STD for RCP85 is only visible.

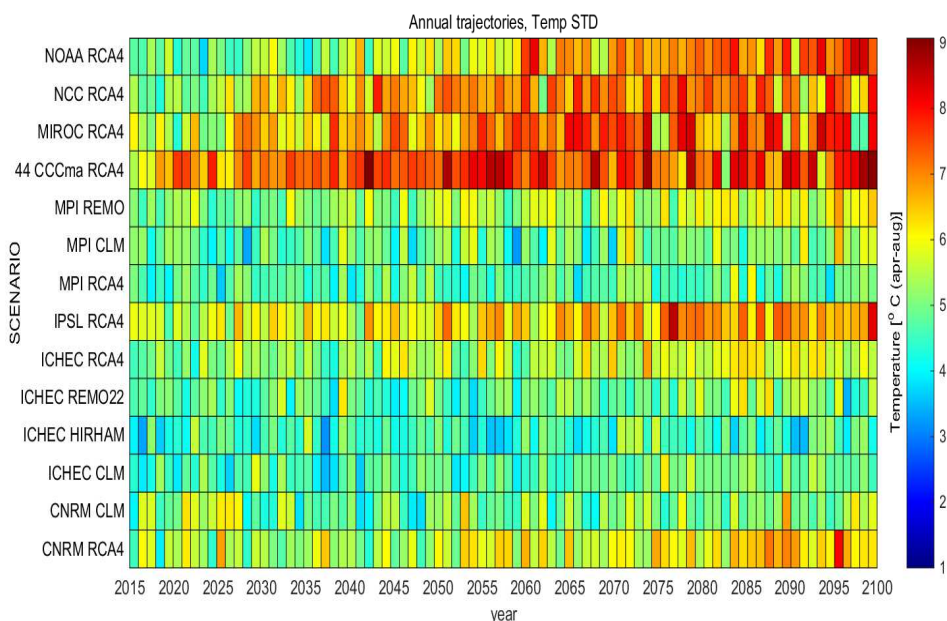


FIGURE 4.10: STD of the annual temperature RCP85, regarding the irrigation period

Short summary of the raster plots After showing the plots, a short summary table is offered in order to have a general picture about the CC scenarios behavior. Moreover to outline descriptive characteristic of the scenarios.

TABLE 4.2: Descriptive summary of the CC scenario’s characteristics

Resolution legend: EU 44, EU 11

	Hottest	Hot	Warm	Cool	Cold	Coldest
Driest		IPSL_RCA				
Dry	CCC_RCA	CNRM_RCA		MPI_REMO		
Average			ICHEC_RCA	MPI_CCclm ICHEC_RCP26 MPI_RCA All other ICHEC_RAMCO	ICHEC CClm	ICHEC_HIRH AM
Wet		NCC		CNRM CClm	NOAA	
Wettest		MIROC_RCA				

4.2.2 Some other important statistics

As it was defined in Chapter 2 dry spell is a period of days when the precipitation is under certain amount. In our case it is important for the irrigation district of Muzza region in order to locate sequences of days that can harm the agricultural cultivation, and in that sense to perform mitigation, or optimization of the water supply management policy. There are few indicators associated with the dry spells. Different authors used different threshold to define dry spell. The most common one, adopted by many meteorological association around the world is: *precipitation threshold below 1mm/day, counting 6 consecutive days*. Considering our case study we consider the Muzza region, taking Rivolta meteo station as representative one. Thus the show results are performed using the grid point from the model that is chosen according the proximity distance to the discussed station. Considering that we performed annual downscaling, reasonably is to consider just the period when irrigation is continuously performed, from April until September.

The importance of this statistics is to show if the mean temperature and precipitation are sufficient enough to describe the main characteristics of the CC scenarios. In other words the chaotic climate variability might trick the statistics and significantly disturb the agriculture causing long heatwaves accompanied by dry spells. These graphs offers a presentation of possible extreme events during the simulation horizon that will help in understanding the system response to the CC inputs.

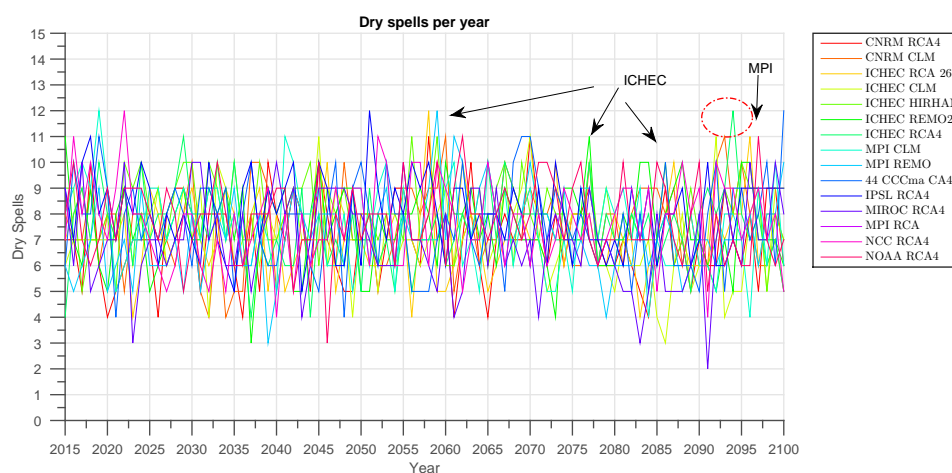


FIGURE 4.11: Number of dry spell trough the year,RCP45

Figure 4.11 represents the frequency of the dry spells through the horizon of 100 years.

It can be seen that even though scenarios associated with the lower resolution are represented as the hottest scenarios, the CNRM EU 11 give us the highest number of dry days through the horizon. However if we double check table?? we will notice that the longest dry spells are related to low resolution scenarios. Another remark goes towards the dry spells, in fact EU 11 performs more dry spells instead, also it can be noticed that the scenarios that show relatively we years like NCC and MPI CCLM, indeed have higher dry spells trough the horizon. The graph shows that there is of increasing the

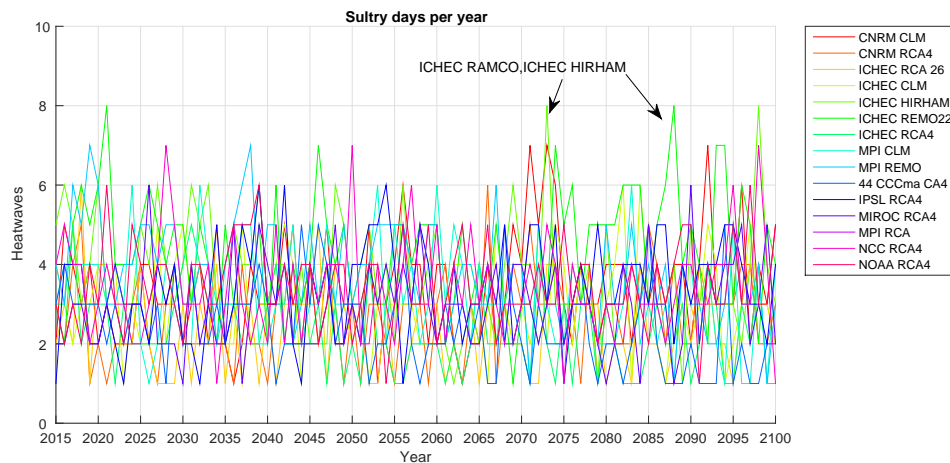


FIGURE 4.12: Number of sultry days trough the year,RCP45

number of the heatwaves, but the magnitude does not treat the agriculture significantly. Additionally comparison has to be made if there is overlapping between the dry spells and the heatwaves and to proceed mitigation, if necessary. Another important note is that the heatwave are more emphasized in the EU 11 scenarios arrays, discarding the fact that the trend of intensive warming, demonstrated by drastic change of the mean temperature intended of the century, is more a characteristic of EU 44, considering the previous graphs. The marked area in the figures emphasized the above concluded fact, that the so called average(check table 4.2) perform longer dry spells and heatwaves than the hot or dry scenarios.

The figures 4.13 and 4.14 will present the behavior of the chosen subset of RCP85. The purpose is the same, exploring an additional interesting behavior in order to asses and possibly eliminate more scenarios, thus to ease the computing procedure but not to increase the uncertainty of the future climate behavior.

Generally the conclusion is the same the high resolution scenarios perform more dry spells and dry days instead. In fact it can be seen that even MIROC, which stands

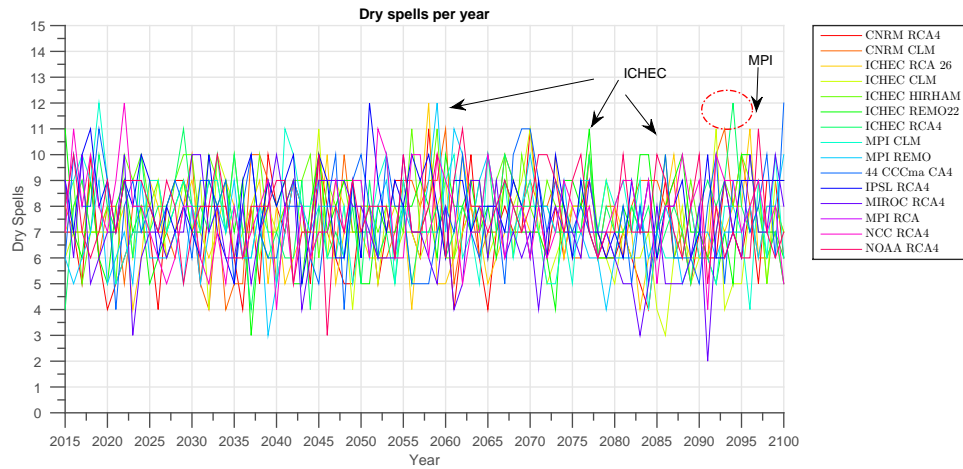


FIGURE 4.13: Number of dry spell trough the year, RCP85

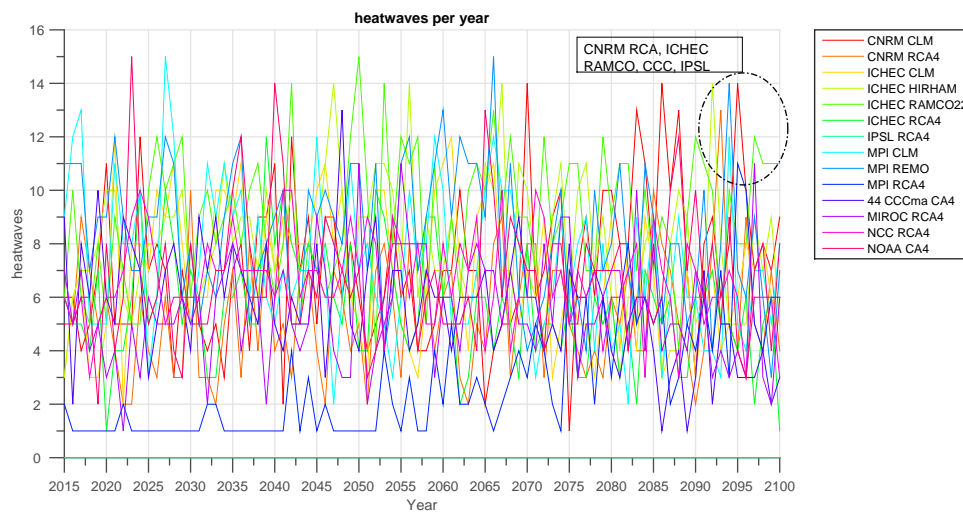


FIGURE 4.14: Number of sultry days trough the year,RCP85

as the wettest scenario, produces more dry spells comparing to the dry scenarios (MPI RCA, CCC, IPSL). As it was seen in the graph 4.12 for RCP 45, the scenarios with high resolution exhibit more heatwaves and more hot days in average than the EU44, beside the fact that CCC and MIROC predict the highest mean temperature. This implies that in average the low resolution scenarios have lower temperature but, the heat waves might be more dangerous for the agricultural cultivation, especially for some sensitive crops.

4.2.3 Temperature anomalies

A *temperature anomaly* is the variation between a particular temperature for a particular station and a particular month, and the average for that month for a selected baseline period. For instance, we use 1993-2007 as a baseline. This is not the best representation of the temperature anomalies, since it is required more data in order to distinguish between natural variability and climate change trends. Why are anomalies used rather than absolute values? This type of statistic is quite common in analysis of temperature increase, or global warming. There are several reasons why we use this:

1. To say that the absolute mean temperature for a particular station in a particular year and particular scenario is, i.e. 17C is pretty meaningless. To be able to say it is 1C more, or less, than a baseline period carries more meaning. In general the representation of the temperature through the projections or historically usually is presented with this kind of temperature change.
2. Temperature anomalies can be compared on a year by year basis, in a way in which absolute numbers cannot, e.g. to that 2050 was warmer than 2060 is meaningless. To say that both years were colder than "normal" tells us something.
3. One big advantage of anomalies is there is correlation between anomalies within a region, although there may be disagreement over just how far this pertains. In contrast, absolute temperatures can vary significantly over short distances, because of factors such as altitude and geography. Who decides which baseline to use? This is quite sensitive question, hence one can claim that the baseline should be shorter and to be changed as the years goes by. In our case we are forced to use this baseline, since it is the same for entire research, and the only available. However, the WMO recommend that the most recent three decades should be used as the "climatic norm", i.e 1981-2010.

As it can be seen the RCPs temperature change envelopes are different. Lower emission performs lower changes, exhibiting range of 5C, while RCP85 reach range of 8 C. Also RCP45, does not show straightforward inclination of the trajectories, thus around the 21th century slightly it falls down.

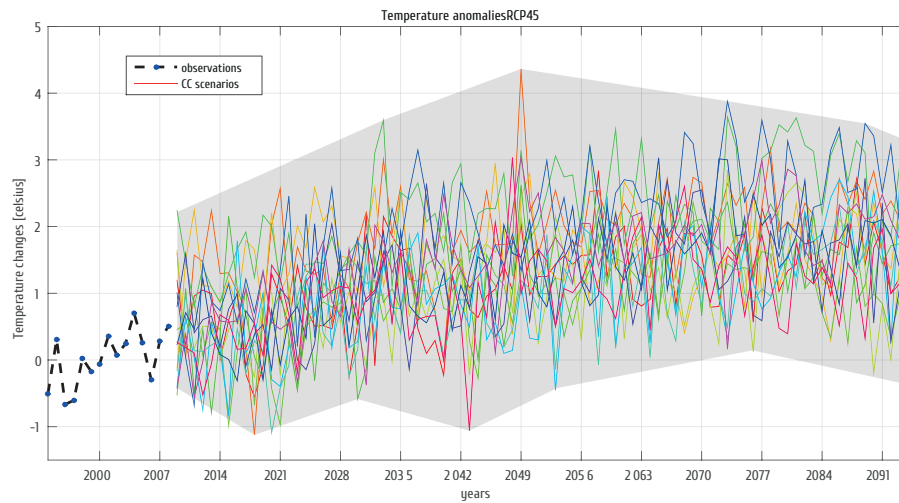


FIGURE 4.15: Temperature anomalies, RCP45

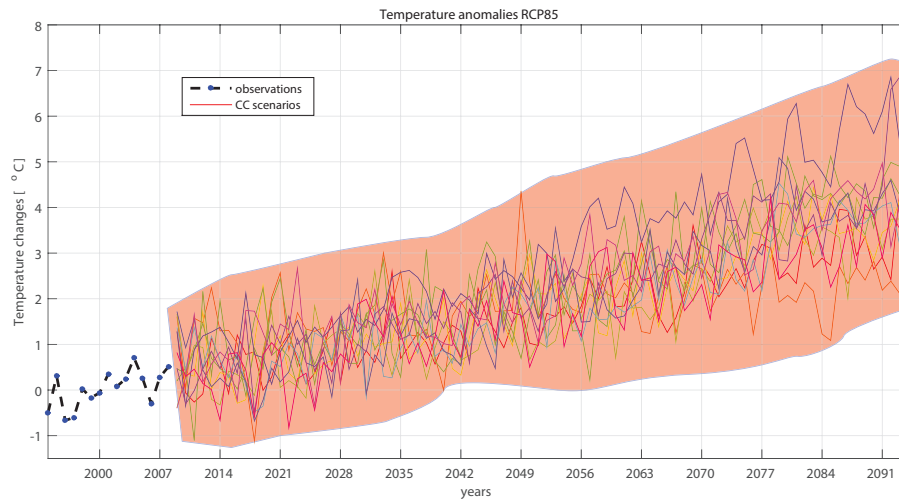


FIGURE 4.16: Temperature anomalies, RCP85

4.2.4 MASH (Moving average over shifting horizon)

The last statistics done in order to assess the scenarios is related to the trend variation, on seasonal and annual level. The techniques offers to the researcher to cope with the interannual variability and seasonality in same time. The goal of using this technique is to assess variations in the seasonal pattern of the precipitation and temperature. When averaging, we consider data over consecutive days in the same year, and over the same days in consecutive years. However, the horizon of consecutive years is progressively shifted ahead to allow for any trend to emerge (Anghileri, Pianosi, Soncini-Sessa, 2014) [24]. The MASH is a matrix, as represented in the figure 4.17. The figure also illustrates how

it works, the comparing with the original time series.

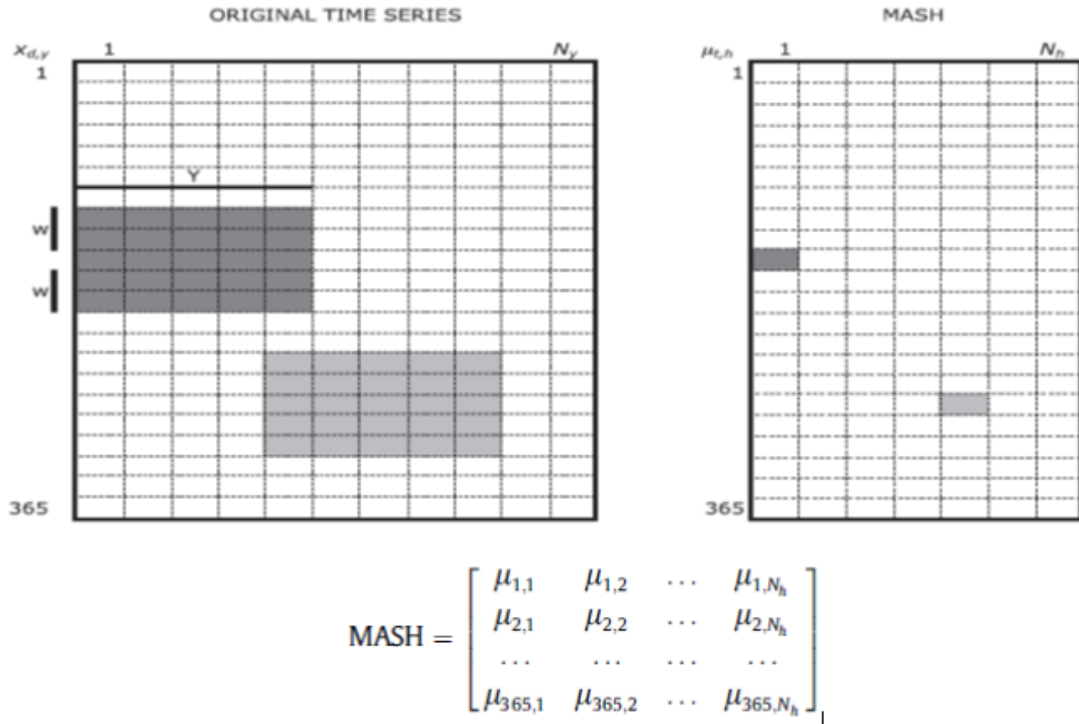
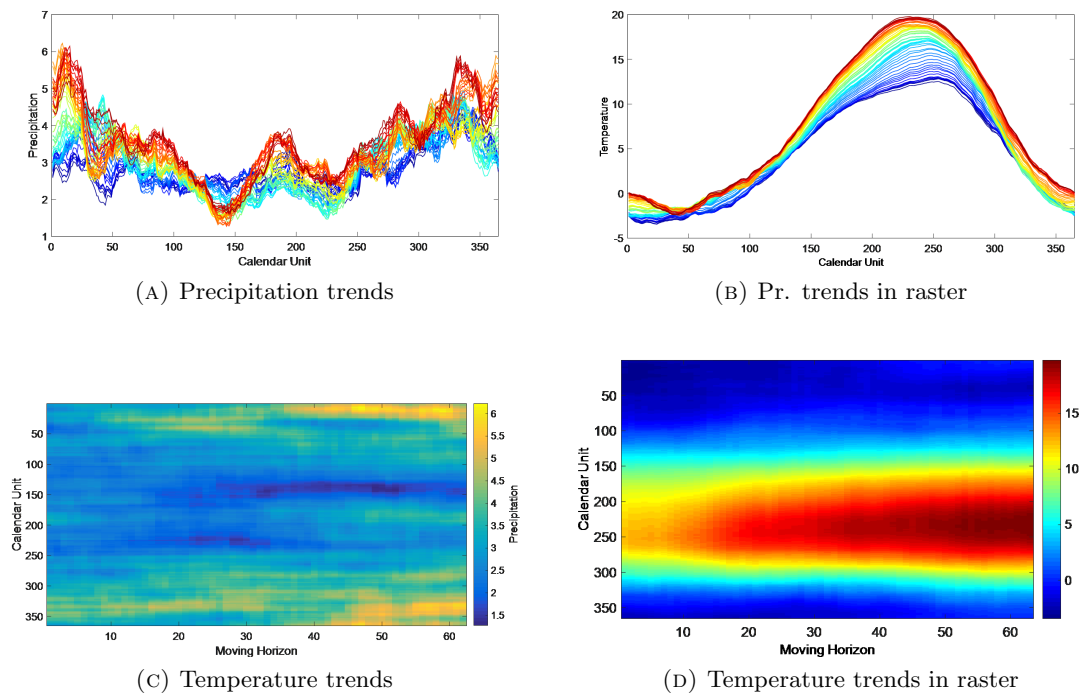


FIGURE 4.17: MASH working scheme and matrix

Therefore later quantification of the trends is easy to be done using some methods like Mann-Kendall. The MASH is a collection of trajectories of the moving average over 'w' consecutive days (or weeks, months, etc.), computed on a shifting horizon of 'Y' consecutive years.

Having these two parameters in front, maybe present the main disadvantage of this technique, having these tuning parameters. Anyway in the present literature regarding the smoothing techniques for trend detection, almost all offered methods require a priori parameters establishment, or posing some parameter space where they can vary. Whenever you deal with parameter uncertainty sensitivity analysis is recommended. Therefore the sensitivity analysis was proceed considering few "most exciting scenarios". The following table represent the analysis results without deeply commenting it. The fields that are filled with the names of the scenarios that deem that combination of parameters offers acceptable, visible representation of the trend variability, in a sense that the trends are easy distinguishable for the associated combination of CC models. For the purposes of this analysis more than 500 graph are produced. After double checking with all the rest of the scenarios, the most interesting parameters combination were observed

FIGURE 4.18: IPSL RCP45, MASH trends for $w=10$ days, $Y=25$ years

additionally. *In the end $Y=25$ years and $w=10$ days was chosen as most convenient combination, beside some EU11 s that were more lean on $Y=35$ years.*

For instance Figure 4.19 show representative graphs from the two available resolution, associated with the two concentration pathways. Being keen on the conservative engineering practice, we will present the most extreme scenario IPSL, as the ones that will be used in the model simulation and optimization. As expected speaking of water resources the worst scenario would be the hottest and the driest. The figure above represent the RCP45 with the worst scenario performance, given by IPSL RCA.

As it can be notice on the left side we have the trends related with the precipitation and on the right we have the temperature. The upper representation give us picture of the trends during the years, considering $Y=25$ and $w=10$ days. As the window is moving we have 62 associated horizons, the blue ones are older and the red are representing the end of the century. The graphs below represent different perspective of representation using raster plots. From both types it can be seen that the precipitation performs significant trend of increasing through the years in the end and the beginning of the year. The trend of decreasing is visible in the early spring, in a sense that the peak is entirely shifting, which is practically expected since we have earlier snow melting (typical for most of the GCMs). Additionally we can see that through the years we have

more intense peaking, especially in the summer. The temperature is behaving quite expected. We have strong trend of augmenting the hot periods, especially the summer time.

However, later we are going to see that even though IPSL represents one of the most intensive scenarios, it does not perform the worse performance of the chosen objective functions.

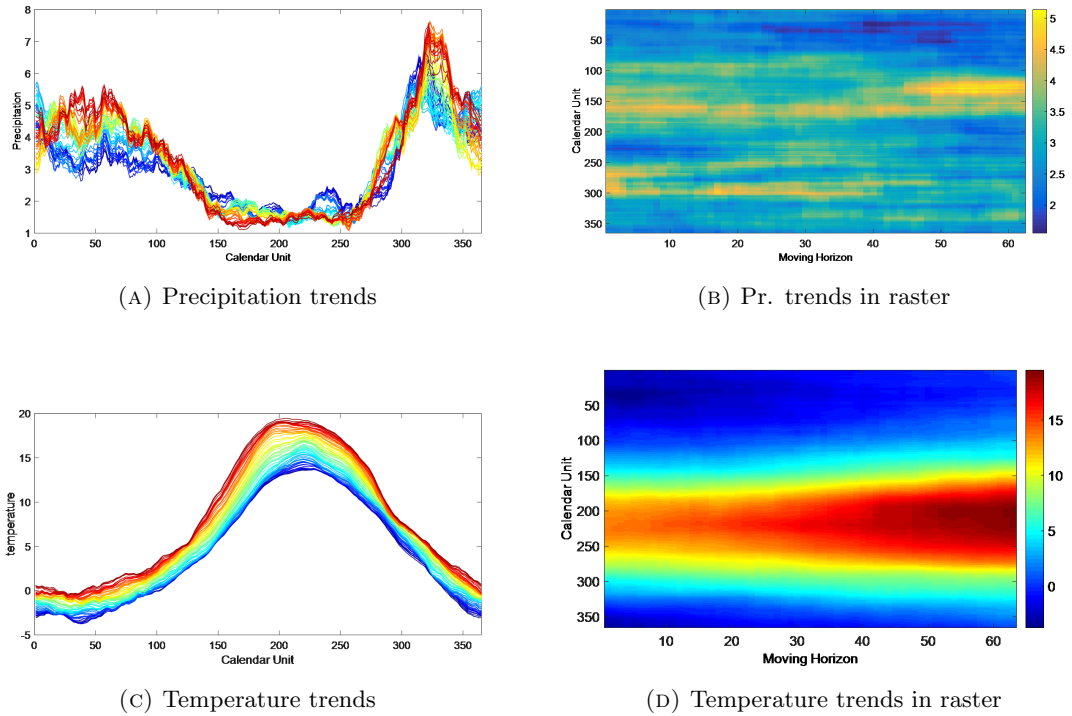


FIGURE 4.19: IPSL RCP85, MASH trends for $w=10$ days, $Y=25$ years

The figures above represent the trend behavior of IPSL RCP 85, but higher resolution(12.5km,EU11). The trends are very similar except the spring peak growing. In the end and the beginning of the year, or during the winter period there is visible trend of increasing precipitation during the horizon, which moves until early spring. Peak shifting is noticeable in the early winter, so the peak is more emphasized and slowly moving towards middle winter. For the rest of the models and comments about the trends we offer the Appendix ??, first part. The conclusion is that trend detection requires further investigation like, trend quantifying. With the presented result we cannot give preference to one or another scenario, except we have more details about the peaking of the precipitation, and about the extreme events. With this information we could help the optimization policy, associating higher weights in the periods of possible flooding, or

vice-versa during the drought towards agricultural yield.

Equally to the analysis above we are going to offer a few more CC scenarios trend analysis.

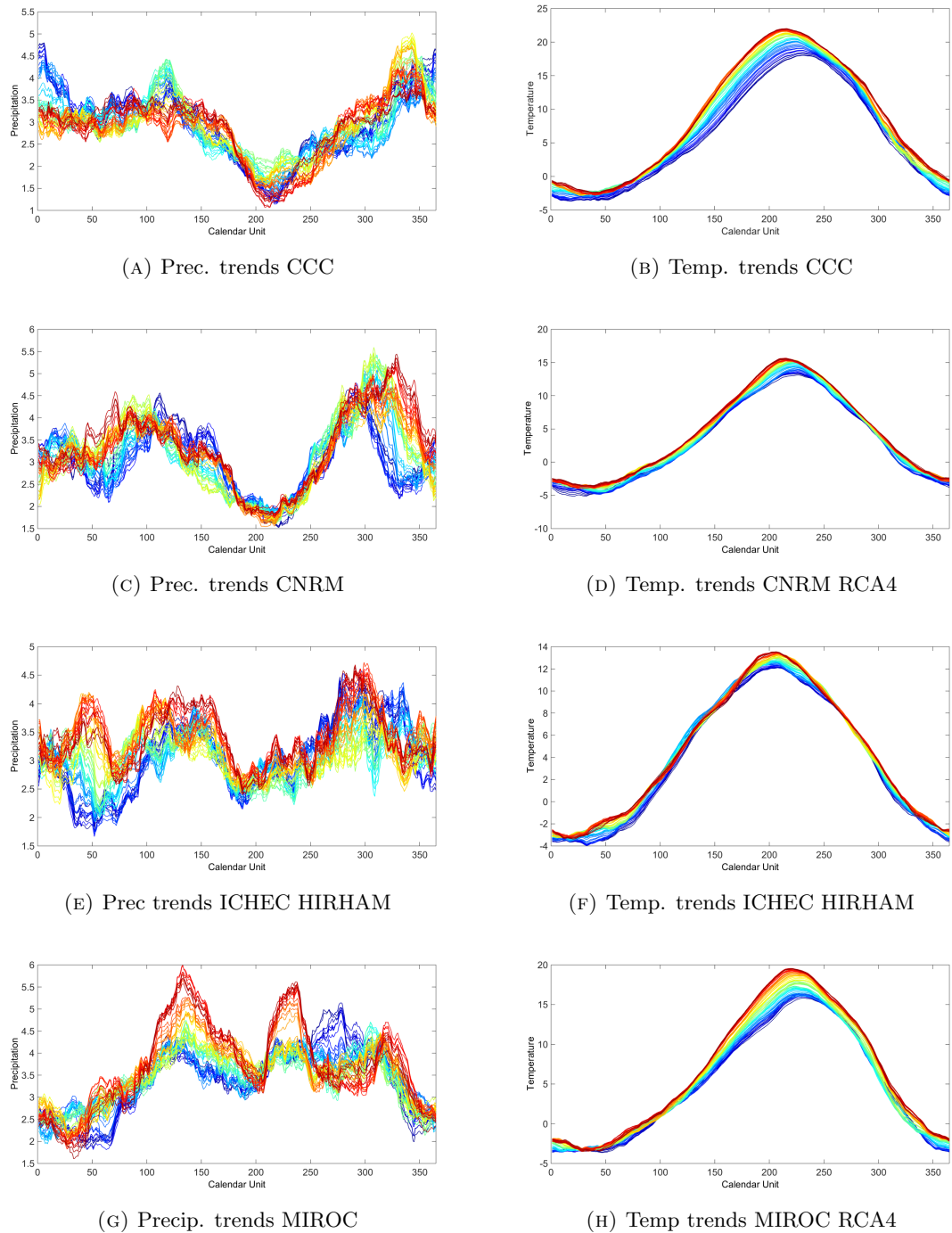


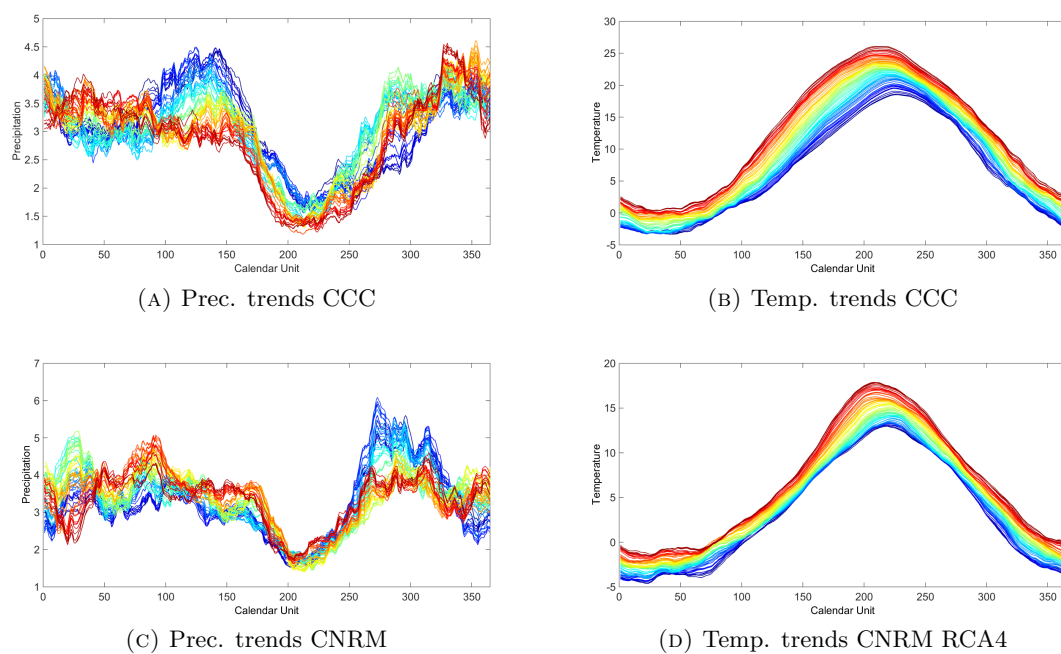
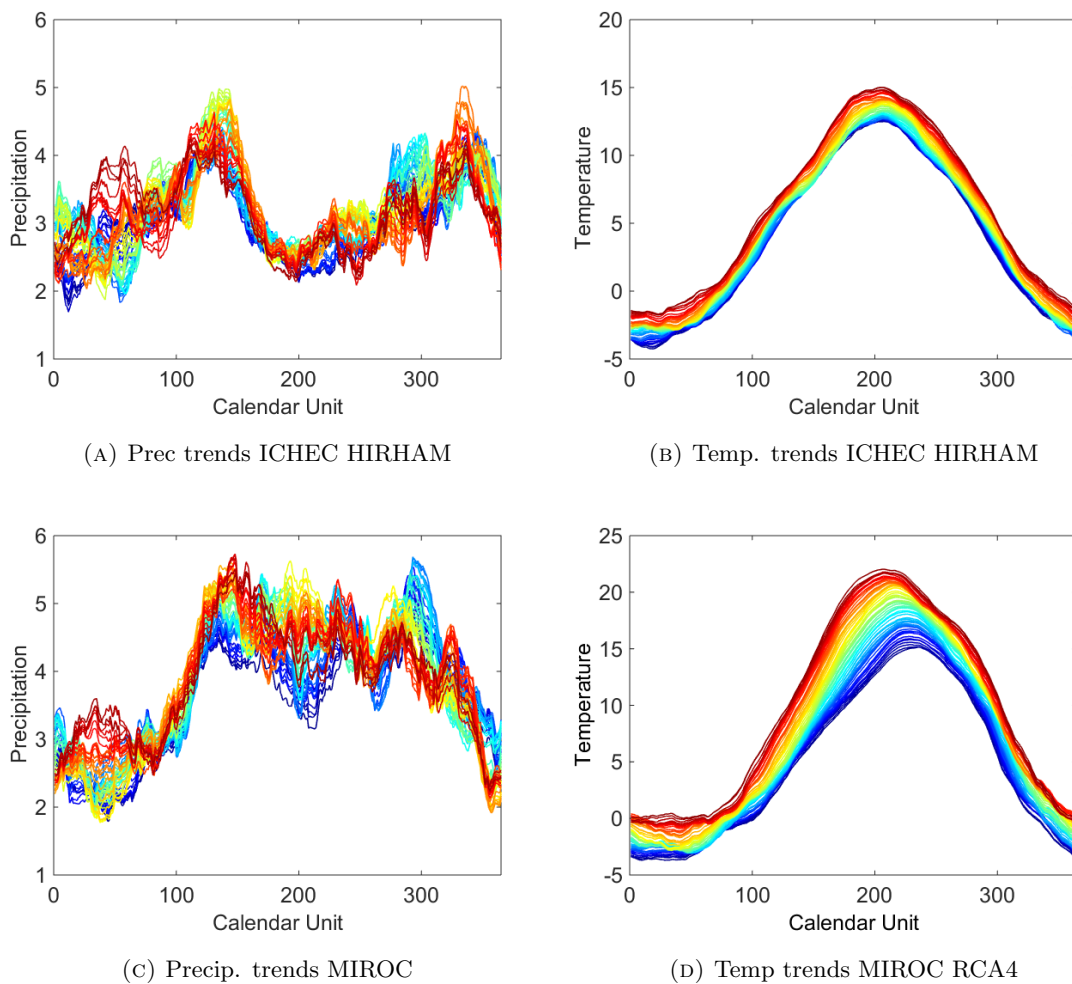
FIGURE 4.20: CCC, MIROC, ICHEC HIRHAM, CNRM RCA, MASH trends for $w=10$ days, $Y=25$ years, RCP45

Comparatively with the previous comments about IPSL, here we present more models,

that will be of interest later on. From fig.4.20 We can notice that the temperature trends are increasing, regarding all the scenarios. Coherently with the raster plots CCC and MIROC perform higher variation between the horizons, ending up with almost 20 degrees mean temperature in last 25 years.

The precipitation trends are indicating different behavior for each scenario. Correspondingly, CCC is quite dry scenario and does not show increase of the precipitation, rather low precipitation in early winter, and flattening the spring peak. CNRM RCA, give leveling up of the mean daily precipitation in spring, and peak shifting in the late autumn, instead. ICHEC HIRHAM performs formation of a new peak in late winter and general trend of increasing the precipitation. Finally MIROC as a precipitation abundant scenario, exhibits strong trend of precipitation increase and peak formation in early autumn and in late spring.

The next figure 4.25 is representing the same scenarios performing a behavior for higher radiative force, namely RCP85. Likewise the previous comments, the behavior of the model is noticeably more intensive regarding the temperature, in the same fashion the precipitation is diminishing. In summary MIROC is again the most abundant, CNRM and ICHEC are exhibiting peak formations, the first in the early spring, later in the late spring and early winter. In comparison with RCP45 CNRM, show trend of decreasing the average horizon value in early winter. CCC is generally decreasing except for the winter time where slightly amplifying trend is noticeable.

FIGURE 4.21: CCC, MIROC, MASH trends for $w=15$ days, $Y=25$ years, RCP85FIGURE 4.22: ICHEC HIRHAM, CNRM RCA, MASH trends for $w=15$ days, $Y=25$ years, RCP85

4.2.5 Inflow trends

Since the inflows are used in the further modeling and optimization it is suggested to give a short overview of the extreme scenarios inflow trend, produced by the HBV model. And give a short timeline comparison. There we are representing the IPSL again, as scenarios that over cross the both resolutions and RCPs and in same time it gives one of the driest and hottest scenarios.

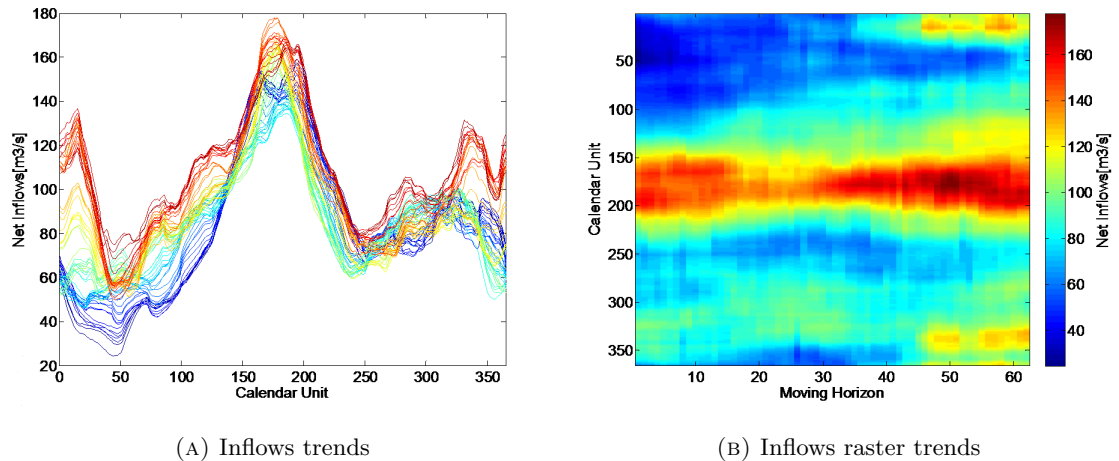


FIGURE 4.23: IPSL rcp45, MASH inflow trend representation, $w=10$ days, $Y=25$ years

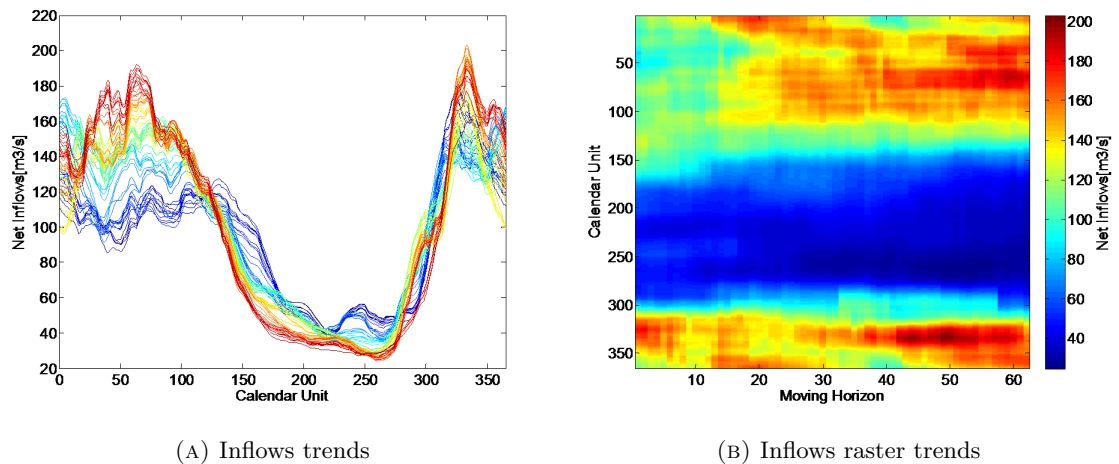


FIGURE 4.24: IPSL rcp85, MASH inflow trend representation, $w=10$ days, $Y=25$ years

The both resolutions perform significantly different behavior, which is expected since we deal two different resolution and two different pathways. The procedure of MASH was explained above so, the parameters we chosen accordingly the sensitivity analysis done

for the precipitation, $Y=25$ years, $w=10$ days. The plotted results show that RCP45 predicts higher peaks and general increase of the total inflow. Therefore formation of an intensive flow can be expected in the early winter in the end of the century. This might induce new floods in that period. The spring flood peak of snow melting is quite stable trough the horizon with a slight increase. The RCP85 represent the CC more precise, hence we have peak shifting from late spring to early spring or late winter trough the horizon, which is quite expected due to the temperature increase. Also the summer inflow suffers with less abundant discharges, reaching only $30\text{m}^3/\text{s}$ in August. However more comprehensive approach for analyzing the inflows is beyond the scope of this study. In fact here we have to relate the origin of the inflows, precipitation and temperature, evapotranspiration and HBV calibration, validation, performance in total. It can be noticed from the precipitation that it coincides with RCP 45increase and RCP85 spring decrease. Furthermore we should approach to our main goal, trough commenting the above mentioned indicators, and therefore see the entire performance of the lake system.

Similarly as the previous section we offer extensive representation of the inflows for the considered scenarios, regarding both pathways RCP45 and RCP85. In final analysis if the input variables we can conclude that CCC RCP85 definitely produces the lowest mean inflows and the trend of dropping down the mean inflows is more than obvious. Thus it is expected CCC to give one of the worst performance for the irrigation indicator. On the opposite CNRM is exhibiting general increase of the inflows trough the years and new peak formation in the late winter, jointly with the early spring inflow peak. Similar happens with ICHEC. However if we consider our simulation horizon (meaning the last, the most red horizon line of the plots), we can define CNRM as the most abundant one among the ones with EU11 resolution. MIROC RCA4 as the "wettest", demonstrate the highest inflow peak and general increase of the inflows trough the horizons. Notwithstanding with last statement and the performance of the irrigation indicator is that beside the high peak, in the early spring and late winter it give the lowest trough. Consequently we do not expect the deficit depleting best performance, neither significant floods, since the peak is in the beginning of the top irrigation period.

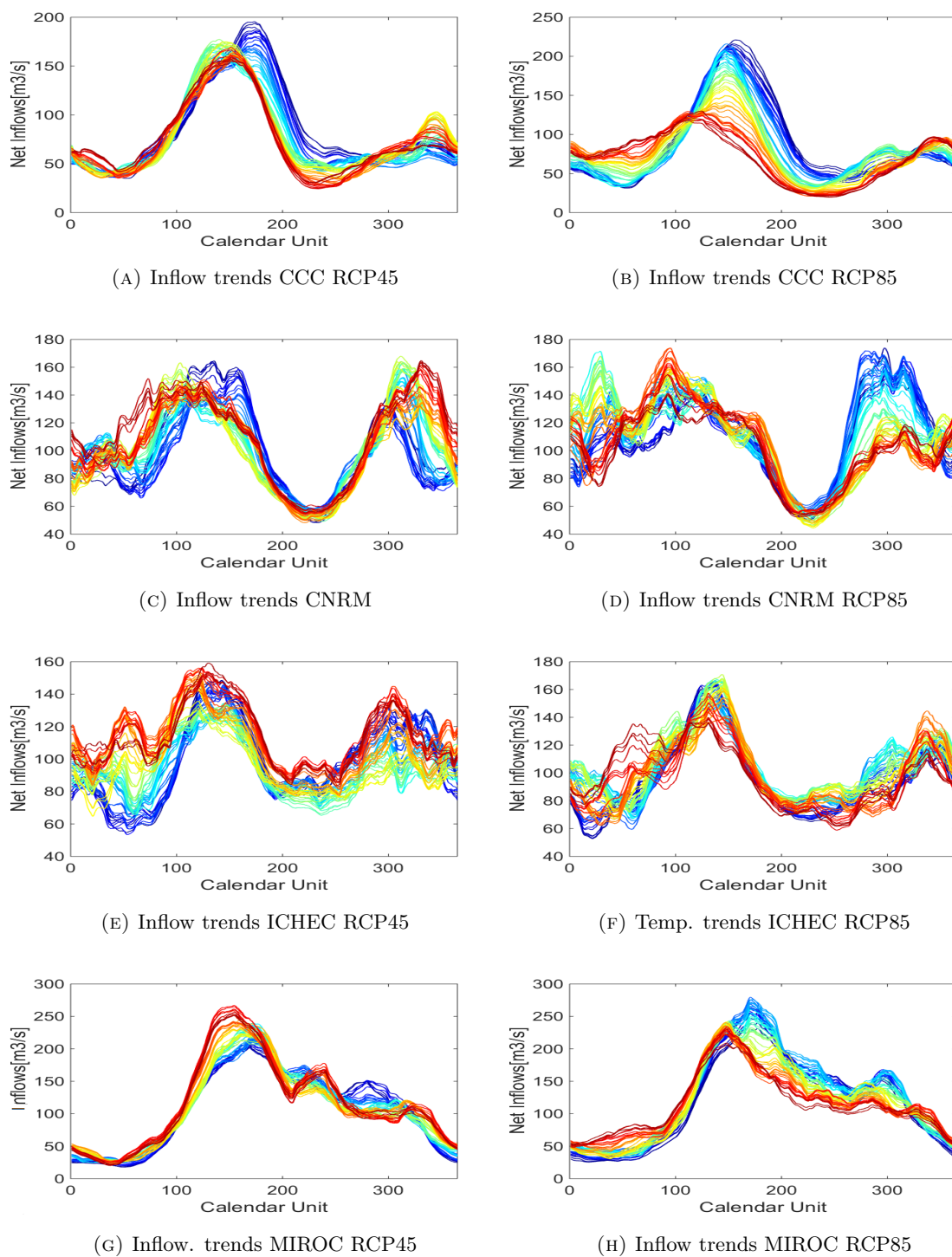


FIGURE 4.25: CCC, MIROC, ICHEC HIRHAM, CNRM RCA, MASH trends for $w=15$ days, $Y=25$ years, RCP85

4.3 Baseline simulation trade off [Uncertainty in the lake operator's behavior]

As it was anticipated in the previous section the experiment starts with observing the uncertainty of the lake operator. To do so, we consider the baseline data and the feedback of the farmers. One shall bear in mind that we are modifying the current situation and checking the operator decision-making behavior. To avoid confusion, in chapter 2 we describe the baseline performance, trying to represent the real situation, considering normative demand. Here we are going to allow the re-optimization of release policy by including the district model results, in addition to the new water demand produced in the end of each year. Any co-adaptive strategies of farmers (e.g. crop rotation) are not taken into account in this experiment. In other words, it is a strictly deterministic simulation, without planning measures, meaning that the cropped land proportion remains the same each year. In fact we are re-optimizing the work of the operator and in that sense we can assess his performance in the past and define the hypothetical improvement that might be used in the future. During the comments in this study it may happen to denote this baseline experiment as adaptive deterministic simulation, which again assume farmers feedback, and none additional co adaptive strategies.

4.3.1 Description of the indicators representation

Aforementioned suggests that we formulate a decision making control problem, faced by the Lake Operator and multi-objective optimization technique in order to derive the Pareto frontier, or the upper bound performances of the system that may help the decision maker. In fact we have the overall farmer's revenue on one site of the loop and 2-dimensional optimization with water deficit and flooded area on the other site. They are used to define the design problem and the objective functions that are optimized using the SDPs and weighting method. Having the MO design problem for the lake release policy we trace back the MO problem to single objective using the weighting method (3). Therefore we considered different combinations of weights in order to explore the Pareto Front, or to define the set of optimized values. For each combination we get different values of the indicators and with that we define different policy for the lake release. Here we open a space for discussing the operator behavior and the possible

decision he can make, in same time to see the effect in the Muzza district. Therefore

TABLE 4.3: considered weights in the re-optimization procedure for the baseline

$W_{_irr}$	1	0.9	0.8	0.5	0.3	0.2	0.15	0.1	0.05	0.025	0.01	0
$W_{_flood}$	0	0.1	0.2	0.5	0.7	0.8	0.85	0.9	0.95	0.975	0.99	1

we are going to represent the values of the indicators considering different combinations of weights (table 4.3) delivering different values of the indicators. The basic simulation horizon is eight years, on annual basis (365 days, with one day time step), meaning that we produce indicators associated with the general horizon, in relation from 1999 to 2007. Therefore the aggregated indicators are represented as:

$$\sum_{i=1}^j \frac{\sum_{i=1}^{365} (g_i)}{365} \text{ horizon sum of daily annual mean indicator, associated with fig. 4.26} \quad (4.3)$$

$$\frac{1}{H} \sum_{j=1}^H \sum_{i=1}^{365} (g_i) \text{ horizon mean of annual sum indicator, associated with fig. 4.27} \quad (4.4)$$

$$\frac{1}{H} \sum_{j=1}^H \frac{\sum_{i=1}^{365} (g_i)}{365} \text{ horizon ean of daily annual mean indicator, associated with fig. 4.4} \quad (4.5)$$

,where H is the simulation horizon, for 365 days per year and i stands for the certain day, j stands for a certain year. The point of using different representations is to show more reliable data representation, i.e how much is the yearly water deficit or the total flooded is, on annual level, as well on a daily average scale, and finally the entire horizon water mean daily water deficit. It has to be noted that here in the optimization we use historical inflow data, whose probability distribution function is assumed to be a lognormal, in order to calculate the transition probability between each state. Thus one can say that this are not necessarily optimal Pareto boundary, since historical inflow is used to determine the bellman function. In this case we will call them Image Pareto frontiers associated with baseline (Anghileri et al. 2011) [2]. Moreover the representation is given in 10 years not sliding window (blue connected solid filled circles), and from the figure ?? it can be seen the enveloped values of the indicators through the period of simulation. The filled points are mean representation of the annual sum of the performance indicators and it clearly demonstrates the entire behavior of the operator. Later having the historical point we will discuss the possible improvement. The other connected frontiers (fig. 4.26) represent the same formulation of the objectives, but for sliding 5 years horizon. The

range and the values of the performance indicators are related with the formulation (eq.4.4), given water deficit (I_{irr}) in $(m^3/s)^2$, and the flooded area (I_{flood}) in m^2 . The main Pareto frontier is represented using the explicit values of the indicators, considering that it is more intuitive and reachable for the audience.

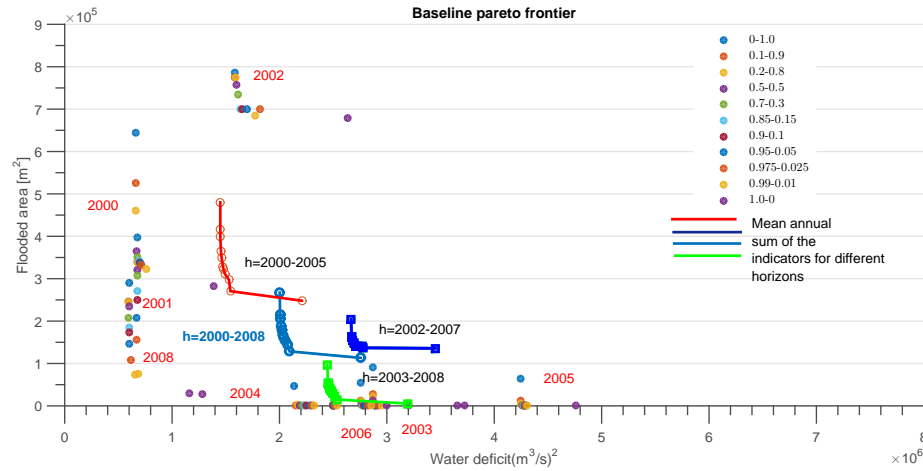


FIGURE 4.26: Pareto Frontiers, sliding horizon, representation of eq.4.4

From the figure above it can be seen that each year (solid disconnected circles) forms different frontier depending of the conditions in that year. It is visible that the floods were most intensive in 2002, but the 2005 is the driest year.

However the normalization will be done only for this section in order to show that the units of the indicators, or the formulation of the indicators influence the range of the weights that are associated to. It is worthy to comment again that the water deficit indicator is squared in order to emphasize the management controls that show high percentage deficit, while allowing small shortages of deficit that would not cause big damages to the crops.

4.3.2 Commenting the Pareto Frontier

Using The Graphical representation of a scatter is suitable for describing the Pareto efficiency and in this case discussing the uncertainty of the operator, instead of looking only in the set of points. The connected points of the Pareto frontier represent aggregated indicators through the horizon. This performance indicators are derived after the optimization of the release policy, taking into account the farmer's feedback, which for instance was not a practice in the baseline performance, or the real situation. For that

reason in fig.4.4 the historical point is given and later comparison with the optimized farmers profit and regular one. In this section the comments will be mostly dedicated towards commenting the uncertainty of the lake manager, but also commenting other sources of uncertainty, like simulation horizon and the modeling related uncertainty.

4.3.2.1 Discussing the uncertainty

Assessing the uncertainty due to the natural variability and simulation horizon

In the study site we described the reason, why our baseline experiment starts from 1999, in fact the changes of the farmers divide the work from and before 1999. In this case we are forced to use horizon of 8 years. However we can clearly notice from both figures that the horizon affects a lot (fig.4.26). In fact averaging during longer or shorter horizon might change a lot considering the flood events. E.g if we use shorter horizon from 2001-2006 (green line), in fact there are not significant floods, so in that case the DM can decide to go for higher weights considering the water deficit. Since we do not dispose with high amount of historical data, and in that way to explore a sliding horizon in order to define the uncertainty, this part is only given as a warning of the influence. For this reason we explored a sliding horizon of 5 years, and the results are alarming that the optimal solution is strongly related with the simulation horizon, that results with high level of uncertainty. Another important thing that arises from fig. 4.26 is that short horizons are more sensitive, then the longer one. If you only compare the $h=1$ year (solid disconnected points), $h=5$ years (red, green and dark blue), $h=10$ years, we see how the constructed boundaries are approaching each other. Anyhow the disperse Pareto's related with the separate years are enough to deliver this conclusion. Another important thing related with this issue is that our indicators, formulated in 3 are very sensitive to an extreme events. I.e the flooded area might significantly increase, even if the lake level rise for few cm. Also the water deficit is squared, which means that the high deficits are more emphasized. The last tell us that if the horizon includes some extremely dry or wet year it might significantly slide the frontier, as the red line moves upwards in fig.(4.26) .

Uncertainty of the indicators

As we discussed the uncertainty of the indicators performance comes from the

modeling procedure and observations error. Having the historical baseline interpretation, we give more space to explore the indicators uncertainty, since we are not dealing with natural variability and the socio- economic or emission uncertainty. Therefor following the plots and the definitions of the indicators, we can conclude that the indicators are pretty sensitive to an extreme event or years, in a sense that the frontiers significantly move if there are floods, or the year is considerably dry. In this case we trace back to the uncertainty of the simulation horizon as well. This problem is even more emphasized with CC scenario, where it can be represented if the backcast scenarios are shown. However even in the perfectly modeled scenario, the values are just equiprobable to observations (Royer, 2000), and they cannot be same.

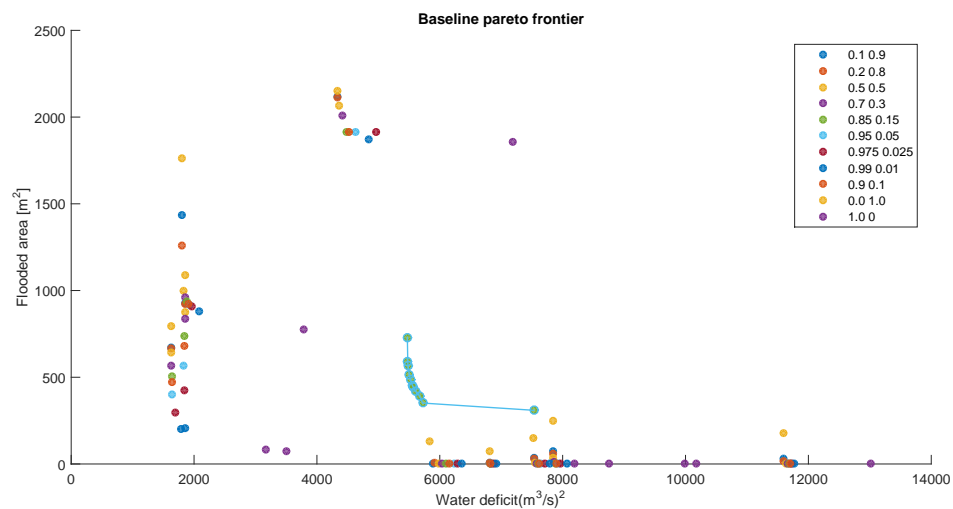


FIGURE 4.27: Pareto Frontiers, more intuitive representation of eq.4.5

Operator uncertainty (uncertainty in operator's trade-off)

The previous figures and figure below can clearly give us some information about Lake Operator behavior. Let us start the analysis with historical point (cross point). The indicators in this case are calculated using the historical inflows, releases and lake levels, and the normative demand mentioned in Ch.???. Accordingly we can notice that the operator was giving favor to the floods, trying to please the closest stakeholders, while the irrigation costs or the deficit was quite high. Some previous studies has shown that the historical point is closest toward weight combination $w_{irr}=0.025$ and $w_{flood}=0.975$, which is true if we consider the old water demand (fig.2.11), and no feedback from the farmers. For instance it can be

notice that the historical value is in parallel line with the mentioned flood indicator point Nevertheless the operator behavior may also have significant impact on the system's performance The frontier suggest that a small change of the weights can cause 1000m² of flooded area. In fact from $w_{flood}=0.95$ till 1 the water deficit change with a biggest pace. Therefore the operator has to be careful with the operation policy. As it was mention before the water manager can behave according the system natural state at the moment, in a sense that there are some years where the floods possibility is 0, so clearly he has to change the operation policy and give favor to the agriculture. The uncertainty of the operator is co related

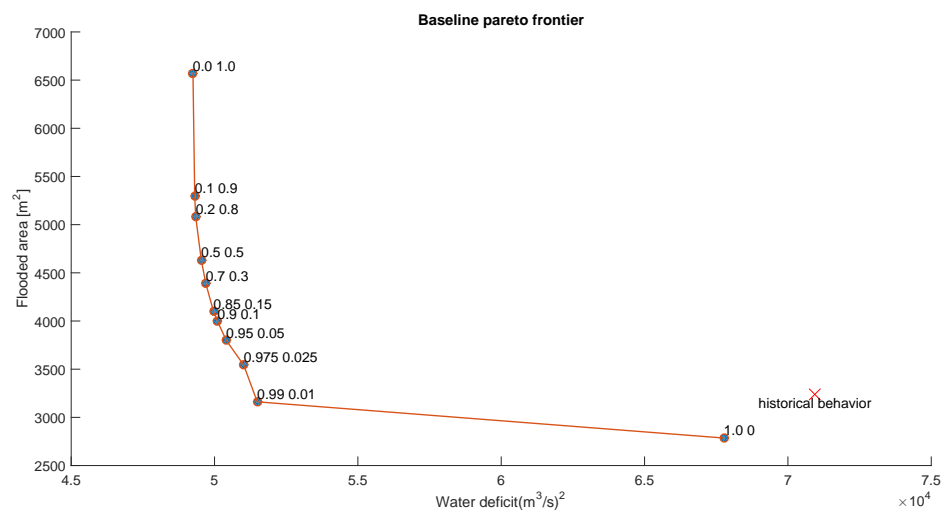


FIGURE 4.28: Pareto Frontiers, Historical behaviour vs re-optimized, representation of eq.4.5

with the natural variability or the lake level, in a sense that the uncertainty of his behavior might be quantified if we look at the historical lake levels, inflows, and additional socio-economic factor, like stakeholder's requests or governmental decisions. It is obvious that the policy can be improved significantly if the lake operator improve his release policy. Here it is clear that his management is based on the lake level data and he does not receive any feedback from the farmers. For instance he open the gates when it is necessary but not required from the farmers. Instead he can release more water during the summer and avoid early autumn and spring floods. This behavior can be noticed in the scatter presented below, where we represent one year historical release policy, red line, and one optimized with farmers feedback. The above mentioned is visualized and without any hesitating we can decide that the operator uncertainty is according the momentous

lake level, and recent inflows. All these suggests that the operator's behavior is

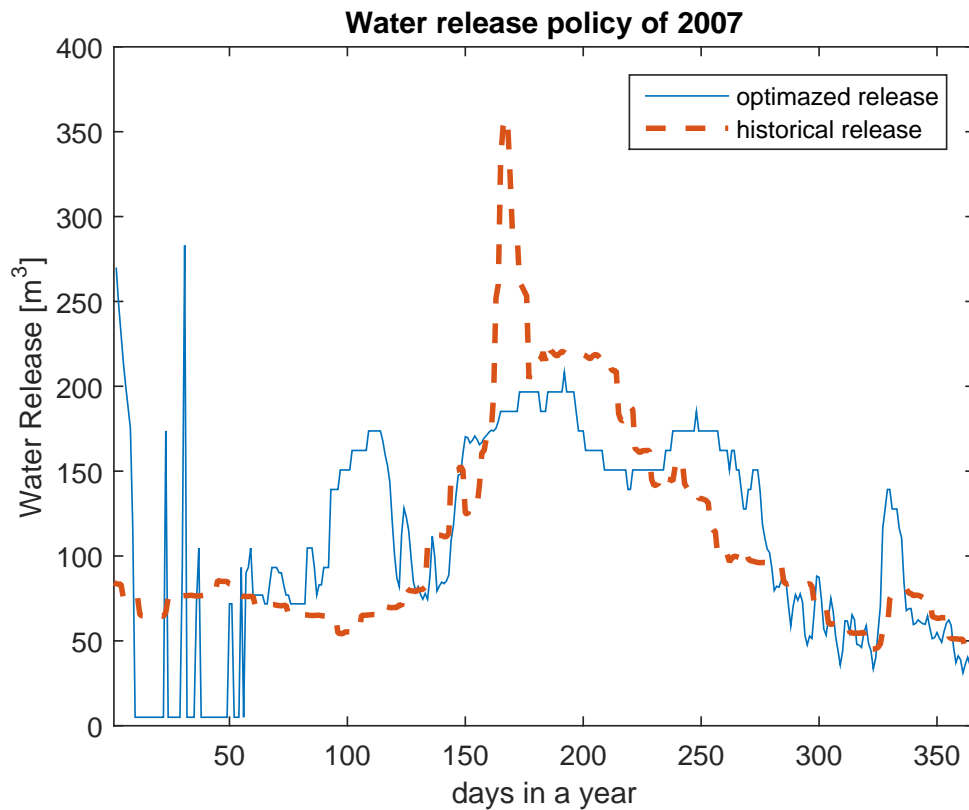


FIGURE 4.29: Water release, re-optimized and historical

dedicated, mostly by the flood events. The influence is also based on historical experience and important events, like floods, that affects her decisions. Therefore, when flood occurs the weighting of the indicators becomes even more factorized by the flooding indicator. However in recent years the WFD suggests IPWRM which includes, communication of upstream-downstream stakeholders. Accordingly it is noticed that the weights are changing in order to retain mutual optima. The discussing In the end it can be concluded that the uncertainty of the Lake operator can be partially quantified if we can assess the:

- Current lake state, or the lake level
- Recent net inflow, which trace back to the natural variability.
- Shore lake stake holders.
- Flood events, historical experience

- Farmers active feedback. If the farmers do not update their demands and requirements, the uncertainty of lower profit and worse management controls is more probable.

4.3.3 Normalization

Until now the representation of the Pareto frontier was explicitly plotting the indicators with their original units, considering more intuitive for the stakeholders. In fact the sensitivity of the assigning weights to the objective functions or the design indicators is exactly due to the difference in the values. For instance it can be noticed that the difference is almost one order of magnitude. To give an more comprehensive picture of the weights we are going to normalize the horizon performance indicators represented in fig4.4. For these purposes simple, normalization method is used where we derive the indicator in values from 1 to 0, vanishing the units and making them comparable. With this we can learn more about the operator uncertainty. There are various normalizations in statistics – non dimensional ratios of errors, residuals, means and standard deviations, which are hence scale invariant. In our case we are going to use normalization so called *feature scaling*:

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (4.6)$$

,where X are the values of the indicators. This approach is dedicated to compare the data with the same units, particularly to see how much the weighting influence the uncertainty separately. And the next one (second columns) is dedicated to compare the indicators between and realize the real weighting.

$$X' = \frac{X}{\|X\|}, \text{ where } \|X\| = x_i^2 \quad (4.7)$$

From the first normalization method, the first two columns, we can comment the range of the indicators variation. For instance the difference between the indicators is more pointed out in the water deficit indicator. That is noticeable even from the graph where the value associated with one for the deficit goes further from the initial front. The flooded area behaves without any significant move from 0 to 1 weighting. This directly goes to the statement that weighting is not actually proportional. Therefore the second normalization give us opportunity to compare the indicators values, thus the

TABLE 4.4: Normalization of the performance indicators output

				feature normalization		vector norm	
weights combinations		Water deficit[m3/s]^2	Flooded area[m2]	Normalized water deficit	Normalized flooded area	Normalized water deficit	Normalized flooded area
0.900	0.100	49308.750	5300.525	0.003	0.665	0.087	0.112
0.800	0.200	49343.647	5080.783	0.005	0.606	0.087	0.107
0.500	0.500	49537.688	4634.154	0.016	0.488	0.087	0.098
0.300	0.700	49693.861	4390.483	0.024	0.424	0.088	0.093
0.150	0.850	49966.917	4097.459	0.039	0.347	0.088	0.087
0.050	0.950	50407.796	3799.513	0.063	0.268	0.089	0.080
0.025	0.975	51018.916	3542.243	0.096	0.200	0.090	0.075
0.010	0.990	51490.218	3161.342	0.121	0.099	0.091	0.067
0.100	0.900	50107.520	3994.430	0.046	0.319	0.088	0.084
1.000	0.000	49248.119	6570.271	0.000	1.000	0.087	0.139
0.000	1.000	67766.258	2785.607	1.000	0.000	0.119	0.059
						1	1

weight combination of 0.85 and 0.15 presumes almost equal representation (i.e. $g_{irr}=0.088$, $g_{flood}=0.087$). Again, we can derive the weights into normalized, so $w_{irr}=0.85$, $w_{flood}=0.15$ would give both approximately 0.5, meaning that they meet with same performance at that point. It is a job the DM to decide if that one is the optimal or not, depending of many factors processes. That is not consistent in order not to cause confusion since the model uses direct values.

4.3.3.1 Profit with farmers feedback (average)

In the previous section we talked mostly about the release optimization and the indicators associated with the lake level and the release policy. However, we deal with a closed loop off line policy, and as it was mention in the introduction we consider 3 performance indicators. In this section we are going to deal with third objective function associated with the farmer's revenue. This function is a product of the district model and communicates with the release optimization trough the water demand (3). In order to compare the baseline performance with and without optimization we are going to represent the profits of the farmers for weighting with ($w_{irr}=0.95$, $w_{flood}=0.05$ and $w_{irr}=0.975$, $w_{flood}=0.025$), as sub-optimal preliminary decision. As It can be noticed from table, the calculated values from the optimization of the district model suggest that as we move towards left in the Pareto frontier (higher water deficit),the farmers gain more money. However the difference is not, significant if we assume that it is

TABLE 4.5: Farmers revenue after re-optimizing the policy

year	Profit-historical	Profit-optimized {0 1}	Profit-optimized {0.5 0.5}	Profit-optimized {0.95 0.05}	Profit-optimized {0.975 0.025}	Profit-optimized {0.99 0.01}
1999	€ 36,894,700.00	€ 36,894,700.00	€ 36,894,700.00	€ 37,032,100.00	€ 37,041,500.00	€ 36,894,700.00
2000	€ 34,335,600.00	€ 35,917,500.00	€ 35,637,700.00	€ 35,032,100.00	€ 34,700,960.00	€ 34,808,000.00
2001	€ 29,310,100.00	€ 29,521,600.00	€ 29,516,200.00	€ 29,621,900.00	€ 29,555,632.00	€ 29,547,700.00
2002	€ 38,952,800.00	€ 39,467,900.00	€ 39,388,400.00	€ 38,990,300.00	€ 38,841,300.00	€ 38,936,400.00
2003	€ 9,547,200.00	€ 9,028,860.00	€ 9,065,350.00	€ 9,075,360.00	€ 11,116,850.00	€ 9,218,510.00
2004	€ 26,205,000.00	€ 27,021,800.00	€ 27,007,900.00	€ 27,081,300.00	€ 27,122,100.00	€ 27,224,700.00
2005	€ 25,357,300.00	€ 22,359,500.00	€ 22,366,600.00	€ 22,367,000.00	€ 22,364,600.00	€ 22,381,000.00
2006	€ 16,005,000.00	€ 22,359,500.00	€ 11,076,800.00	€ 11,129,500.00	€ 11,257,100.00	€ 11,386,200.00
2007	€ 12,228,200.00	€ 11,094,600.00	€ 19,076,800.00	€ 18,781,900.00	€ 19,051,700.00	€ 19,408,900.00
Horizon sum	€ 228,835,900.00	€ 233,665,960.00	€ 230,030,450.00	€ 229,111,460.00	€ 231,051,742.00	€ 229,806,110.00
Horizon mean	€ 25,426,211.11	€ 25,962,884.44	€ 25,558,938.89	€ 25,456,828.89	€ 25,672,415.78	€ 25,534,012.22

equally divided among the 66 farmers, therefore it leaves space for the negotiation and decision making. It will be easier for the farmers to accept some terms from the lake shore stakeholders, hence the flooded are is considerably changing and the damaged are is significantly important, especially if we consider the touristic cities.

4.4 Baseline performance with co-adaptation

During the entire text, one can notice that few times we are mentioning about co adaptive strategies and planing in the climate change. Furthermore it is also mentioned that some previous studies, already considered this approach and offer different solutions about future better performance of the system.

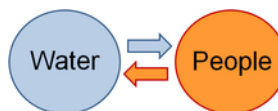


FIGURE 4.30: Sociohydrology

4.4.1 Towards co evolutionary socio-hydrology

Sociohydrology is an interdisciplinary field that assume an interaction between people and water, it establish a continues mutual feedback. It studies the interplay among the human, water resources and nature. The new science of sociohydrology that treats people as an endogenous part of the water cycle, interacting with the system in multiple ways, including through water consumption for food, energy and drinking water supply, through pollution of freshwater resources, and through policies, markets, and

technology. What sets socio-hydrology apart from IWRM is that socio-hydrology explicitly studies the co-evolution of humans and water. It explores the way the coupled human-water system evolves and possible trajectories of its co-evolution, including the possibility of generating emergent, even unexpected, behaviors[25]. (Murugesu Sivapalan, Hubert H. G. Savenije³ and Günter Blöschl^{put})

.The fundamental question we are motivated to answer through application of a socio-hydrological modeling is what drives the human response within the human sub-system. As this study implements, the impacts of land and water management decisions on the hydrological system, in terms of water balance, flows and quality, are presented well with suggested models above. Also the farmers behavior is tackled using the MAS(check App.??). However, the drivers of the human feedback component at a system scale have remained elusive, since it is very hard to define the active interaction between the individual farmers or farmers families using a Computational approach. The effective and comprehensive framework of the sociohydrology assumes 6 steps of different dynamics (population, hydrology, economics, ecosystem, state sensitivity, response) and it is much more complicated than the approached suggested here (check App.C).

4.4.2 Co adaptive planning control

In this section we will show a simple conceptual framework to examine the coupled dynamics of integrated agricultural socio-hydrology catchment systems. Thus we are going to follow the suggested loop in Chapter 3 and include the mentioned crop rotation. Entering the crop rotation we include a planning action in our Design problem, denoted as a planning control (u_p). Therefore we enlarge the problem of the DM, as well. The main principal is that the farmers change the crop in the end of the year, willing to gain more profit. The modeling approach is: among few offered crops with their characteristics, the functional optimization chose the best one for each agent/farmer in order to have higher revenue in the next season. Meaning that beside the feedback of new water demand, the farmers model includes one more planning control related with the crop rotation. In addition the demand is different than the deterministic simulation, and it offers better optimization approach, meeting the requirements on both sides. This means that the farmers will gain higher profit, and the same can give space for the lake shore stake holders to choose. Therefore the water demand problem is being regarding the pre-season decisions of the farmers on the crops pattern u_p . Each irrigation unit,

which represents the decision-making authority in charge of selecting the crop to grow, is modeled as an active agent. The optimal crop pattern can be obtained by solving 66 non-linear optimization problems (one for each agent) based on the dynamic model of the Muzza district described in Chapter 3:

$$\mathbf{J}^* = \max_{\mathbf{u}_{crop}^p} \mathbf{J}(\mathbf{u}_{crop}^p, \mathbf{p}) \quad (4.8)$$

,where $J(\mathbf{u}_p^{crop})$ is the objective function of the k-th agent as defined in 3 as maximization of the farmers revenue, which depends on the agent crop choice $\mathbf{u}_p \in U_p$ and the operating policy \mathbf{p} adopted by the water supply agent. The set U_{crop} comprises five different crops representing the most commonly grown in the Pianura Padana agricultural system, namely *tomato, grass, corn, soybean, and rice*. On the basis of the solution of eq (4.8) for each agent, representing the optimal crop pattern \mathbf{u}_p crop for the entire district, it is possible to derive the actual irrigation demand $w = w(\mathbf{u}_p)$ that the water supply system has to satisfy. Due to the complexity of producing accurate long-term hydroclimatic forecast required by the model to solve eq (4.8) at the beginning of the agricultural season, it is assumed that the farmers have a perfect forecast of the future hydroclimatic conditions. The resulting performance will therefore represent an upper-bound solution. The introduction of forecast errors may result in sub-optimal farmer's decisions and performance degradation. The aim of the proposed co-adaptation strategy is to cross-condition the decision-making problems of the agents (i.e., water manager and farmers), and perform better management policy as well as higher revenue.

4.4.3 Co adaptive trade off

The co adaptation, represented with crop choice of the farmers, and in that way changing the land crop use is only integrated part of our modeling procedure. This presumes that everything remains the same, beside the demand and revenue change. This co adaptation measure afford use better performance of the water deficit indicator. By changing the crops, the water demand is partially adapting towards the hydroclimatic trend in that period and contributes producing a better shaped water demand according the current conditions. It follows that the lake operator has more space to manipulate and to perform better controls.

In order to show this we run also a co-adaptive simulation of the same region for the

baseline historical data, optimizing the two up-mentioned objectives. The procedure is the same, beside the nesting of the planing decision in the Design Problem making it a cascade optimal solution, because the later is in fact considered periodically in the end of the season and that decision stands for the entire simulation horizon of 365 days. Furthermore we use the same weighting method in order to define the the efficient set of optimal solutions, or the Pareto Frontier.

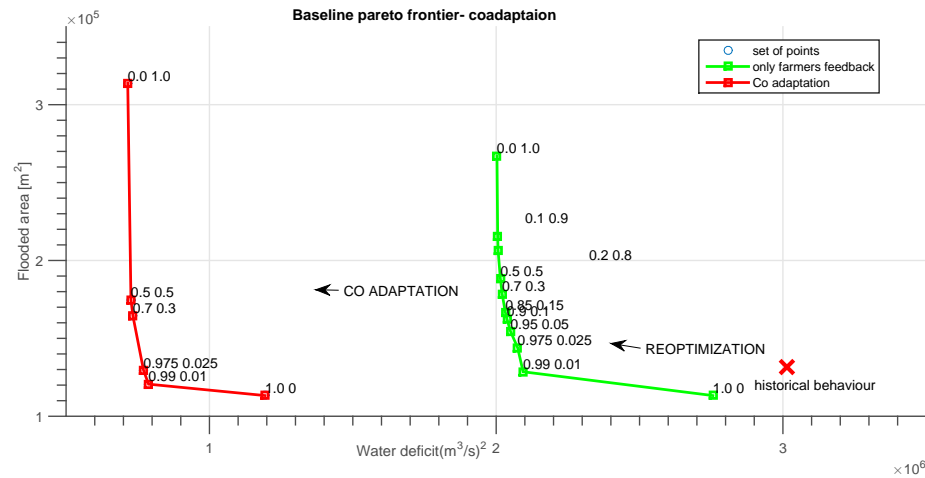


FIGURE 4.31: Pareto Frontiers, Historical behavior, re-optimized, representation, Co adaptation

As it is expected the results from fig.4.31 show significant performance improving, especially the water deficit indicator. The improvement of the indicator is almost one order of magnitude resulting with profit increase of 30 millions of euros table 4.6. From the pareto frontier it can be noticed that, the behavior is the same except we have more extreme flood events if we assign values of 1 to the water deficit. Also the points which can be considered as most efficient and partition in the negotiating process are giving more favor to the flooding indicator, suggesting even higher values of 0.975 for the assigned objective function. In addition the combination of $w_{irr}=0.01$ and $w_{flood}=0.99$ offers better mutual performance for both objectives. This means that if normalization is performed, the equal normalized values of the weights would be associated with higher value of w_{flood} . Here the uncertainty of the operator can be quantified even easier, if we only look the state and the level of Como lake. Table 4.6 clearly show that there is improvement in the revenue, for almost 30 milions comparing the historical behavior of the operator. Anyway, the profit difference is not that important considering the fact that the water deficit is significantly diminished.

In the end of this section, it should be mentioned that this co adaptation action is given

TABLE 4.6: Farmers revenue after co adaptation

year	Profit-historical	Profit-co adaptation (0 1)	Profit-co adaptation (0.975 0.025)	Profit-co adaptation (0.99 0.01)	Profit-co adaptation (1 0)
1999	€ 36,894,700.00	€ 37,113,400.00	€ 37,515,200.00	€ 36,944,300.00	€ 36,698,300.00
2000	€ 34,335,600.00	€ 37,113,400.00	€ 35,999,200.00	€ 36,944,300.00	€ 35,858,300.00
2001	€ 29,310,100.00	€ 30,107,900.00	€ 30,047,600.00	€ 30,105,400.00	€ 29,873,700.00
2002	€ 38,952,800.00	€ 39,864,300.00	€ 39,394,500.00	€ 39,821,600.00	€ 38,943,000.00
2003	€ 9,547,200.00	€ 18,315,400.00	€ 15,228,600.00	€ 17,288,700.00	€ 14,366,500.00
2004	€ 26,205,000.00	€ 28,655,400.00	€ 28,621,500.00	€ 28,645,100.00	€ 28,767,400.00
2005	€ 25,357,300.00	€ 22,575,100.00	€ 22,522,100.00	€ 22,554,600.00	€ 22,308,000.00
2006	€ 16,005,000.00	€ 19,028,700.00	€ 18,957,000.00	€ 18,002,700.00	€ 14,350,470.00
2007	€ 12,228,200.00	€ 22,643,900.00	€ 23,047,100.00	€ 22,710,700.00	€ 22,316,700.00
Horizon sum	€ 228,835,900.00	€ 255,417,500.00	€ 251,332,800.00	€ 253,017,400.00	€ 243,482,370.00

only with suggestive character on order to highlight how important is to consider the additional mitigation measures in the water resources management in improving the management operation policy. The later arises the importance of the interconnection between the social processes and the water resources, moreover it defines the co evolutionary sociohydrology. In this study only the effects of the current situation are defined. Indeed, it give us hints that for the future CC scenarios the co adaptation measures would be much more attractive to implement.

As it follows the crop rotation presumes different usage of the farming land, thus we have change of the baseline land use pattern. Figure 4.32 present the land use in 2007 if the co adaptation is performed, and it can be seen that beside the rotation of grass and maize some farmers have decided to plant tomatoes (red color). This move of the farmers might peculiar since additional expenses are arisen with the adapting the land for tomato farming. Anyway the map shows possible development of the district area .

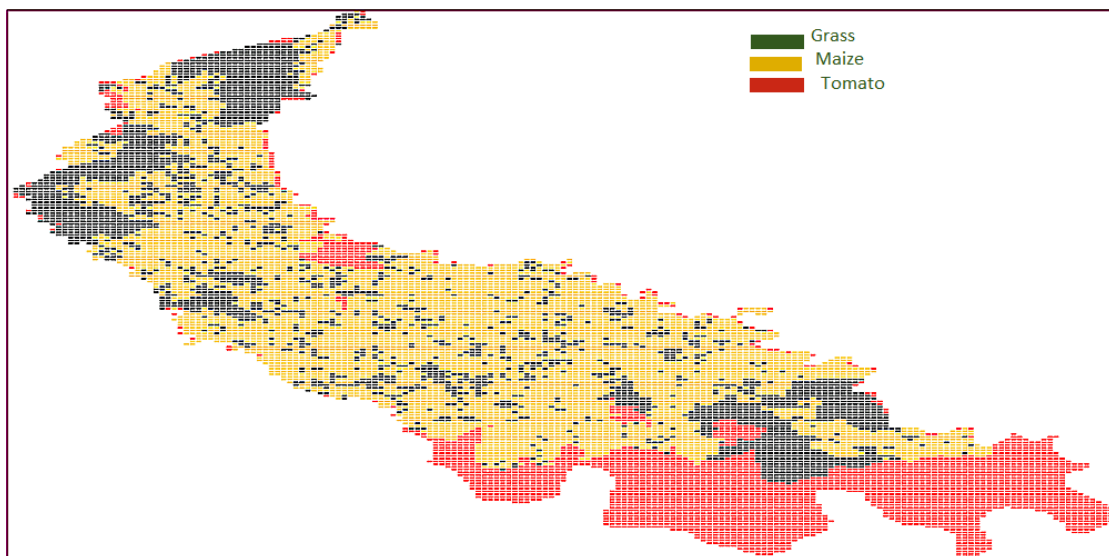


FIGURE 4.32: Baseline Land-use, the green color refers to grass, the yellow to maize

4.5 Climate change scenarios simulation

In the beginning of this chapter we explained how does the experiment is setup. Recalling table??, in this section we are going to explore the CC scenarios related with the assigned arrows. For instance we are going to perform the deterministic simulation for all 22 CC future projections. This presumes that no adaptive,nor mitigation measures would be considered. The simulation starts assuming the initial states same as 2007. One may wonder for this robust assumption, though it would give significant errors to the final results. However this study has not a strict purpose of presenting the real future conditions of this complicated hydraulic scheme, but more to present robust simulation, that will increase the awareness climate change influence. There are few goals of this experiment:

1. To comment the natural variability
2. To explore the future behavior of the system
3. To asses the structural and parameter Uncertainty of the CC scenarios
4. To quantify the socio-economic uncertainty.
5. to explore a possible improvement of the behavior assigning different weights.

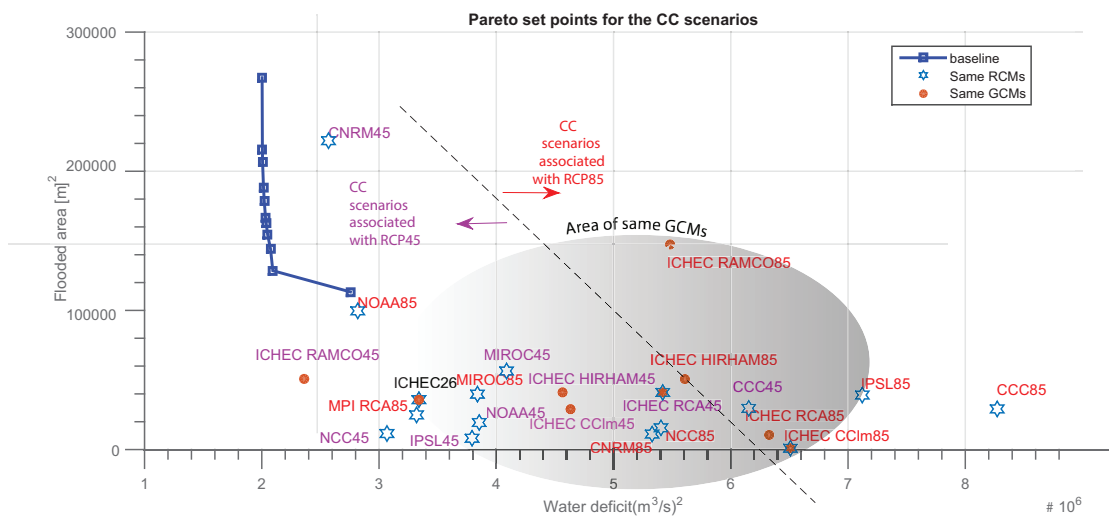


FIGURE 4.33: CC scenarios indicators representation for weight combination $w_{irr}=0.025$ and $w_{flood}=0.975$

Natural variability The uncertainty coming from the natural variability is not the most influencing one (see 4), but if you consider short simulation horizon, it may cause significant changes. Indeed we showed that 5 years sliding horizon might change the management policy. Then, 10 year is less sensitive but still vulnerable to uncertainty. In reference, the plotted values above show the chaotic variability of the CC scenarios. None of the scenarios even associated with same circulation model, or emission pathway, perform similar behavior. Furthermore some scenarios that statistically (check section 4.2) show the drier years among all RCP45 and significantly hot mean temperatures, i.e. ICHEC RAMCO and NCC RCA4 associated with RCP45, in this plot some of those extreme scenarios including IPSL are showing quite good performance for the flooding indicator and not that worsen water deficit indicator, comparing with the re optimized the baseline Pareto. There are two reasons for this trustability issue of the indicators. The first is related with choice of the relatively short finite horizon, which is the intrinsic issue of this assessment and independent of the modeling uncertainty. And as follows the second is the modeling or structural errors. These two reasons are indeed correlated, the natural intrinsic variability affects the chaotic nature of the climate models producing temperature and precipitation trajectories, then simulated into inflows, can only be interpreted as equiprobable (Royer, 2000). In brief, it has to be mentioned that several studies associate this natural variability theory of chaos and the butterfly effect. In relation it is true that the initial conditions might significantly disturb the behavior of the later states. It has been stated that natural chaos in the climate system creates uncertainty in predictions that can not be removed, no matter how good scientist's models get. In the manner of the definition of weather and climate, one can stress that, the weather is an initial Value problem, climate is a boundary Value problem.

In our study we do not go into details, exploring the structure of the GCMs, but it has to be highlighted that the natural variability we notice in the behavior of the EU-ROCORDEX projected climate variables, underlines the initial conditions of the *GCMs calibration and parametrization*, as well as of the regional *downscaling (RCMs)*, and our *QQ mapping* calibration.

Even though here we are witnessing significant partition of this uncertainty, in some more detailed studies (Arnell (2003)) it has been shown that the natural variability is negligible comparing with the projected CC scenarios. In this studies more comprehensive approach was dedicated towards various horizon exploration, extreme events locating and different ranges of natural variability.

Modeling Uncertainty In Chapter 3, we introduced different types of uncertainty and later in the text we defined the one associated with the CC future scenarios. Nevertheless that classification helped, only to understand the sources of uncertainty. Here in this section we will recall some of them, but also we will propose some subgroups of those types of uncertainty. Furthermore, as our physical system assumes, sequence of models, in the end we end up with abundant modeling or structural errors. Despite this, the structural uncertainty is generally high for GCM/RCM models. This stands for few reasons:

1. Limited understanding of the natural processes, like glacier dynamics, ocean, atmosphere, etc.
2. Mismatch in scale between the grid resolution of the RCM and the catchment boundaries.
3. Error induced by using a coarse spatial resolution (e.g. Q1 cannot correct the temporal properties of precipitation time series, like dry spells).

Another important factor affecting the structural uncertainty is the catchment model, or the rainfall/runoff HBV model, mostly because of the oversimplified description of the natural processes and performing an average inflows. For instance in our case it give zero or negligibly small inflow days only if the soil storage is empty (check Ch.3). This is the reason, why we have some strange behavior of some scenarios, i.e. MIROC which is the representative of the wettest scenario gives worse performance than MPI, which is highlighted as the second driest scenario. ICHEC RAMCO also comparably dry scenario, give a better performance, mostly because of the dry spells. The latter can be also questionable for the following case: two CC scenarios with same GCM, noted as ICHEC and same RCM, noted as RAMCO, give diametrically opposite results in reference of the baseline. This is also unexpected if we see the envelope of the GCM uncertainty diversity.

Beside the structural uncertainty, there is so called parametric uncertainty. This one usually arise because of the inability of perfect calibration, or because of lack of data for calibrating or validating the models. Another related paradox is that the models that are producing future projected data are calibrated using historical, past information. The parametric uncertainty is also related with the HBV model and the lake modeling

optimization, moreover with the chosen inflow distribution (as in our case lognormal). If we want to assess the GCM and RCM influence to the modeling uncertainty, firstly we have to give off some hints from the literature. As given in section 4.5, most of the studies associate the GCMs as the biggest uncertain contributor. Moreover some studies suggest that the seasonality is differently influenced by the models, or GCM is the main source of uncertainty in winter time, while the RCM is more important in the summer (Jacob et al., 2007). However if we look at the plotted values we can notice that the variability caused by different GCMs and same RCM (the hexagonal blue empty markers) is huge in it varies in remarkably contradictory performance of the indicators. From significantly water abundant behavior, NCC45 or MPI RCA4, to severe water deficit CCC45.

The last statement can confidentially confirm the initial guide that the GCMs are the major source of uncertainty. The range of diversity due to the different circulation models is much more relevant than the natural variability and the finite horizon choice, or any other intrinsic uncertainty.

Socio economic source (RCP influence) In the physical world modeling the socioeconomic system tackles on population increase, demand increase and emission scenarios. This uncertainty is rather different, since it is quite hard to simulate or reproduce the future socioeconomic events. Even if there is sufficient enough reproducing model, its calibration relies on historical data, which is not entirely acceptable, especially for distant horizons. As we noted the socioeconomic source uncertainty is described by the emission scenarios. Thus three different concentration pathways are offered, as an attempt to assess their uncertainty contribution. Observing the plot above 4.33 it is easily noticeable the influence of the different radiative force related with the future scenarios (check section ??). The dashed line broadly separates the graph into two parts, where on the left naturally less intensive pathway is associated (RCP45, magenta colored names), and in the right part RCP85 is dominating. Although this division is done, there are some exclusions that are out of this limits. This exclusive behavior might be product of higher influence of some other uncertainty sources like the intrinsic variability. It is questionable the performance of the ICHEC RCA RCP26, since it has the lowest radiative force. Finally we can say that commenting the socioeconomic uncertainty is quite broad field and our main focus are the emission scenarios or RCPs. Additionally it is worthy to mention that this source of uncertainty in our modeling procedure is also associated

with the market crop prices and water prices in the future. As well as with the new agricultural strategies and governmental policies like CAP. In reference the CAP subsidies are in fact considered in the farmers model in a very simple notation, giving more profit to the farmers with bigger land size. In future all this elements might change, entirely. In the next section more comprehensive description is offered, exploring the weights trade off for few extreme scenarios and giving some future alarms for lake optimal operation.

4.5.1 Future projections trade off

In the previous section we saw different types of uncertainty that are usual reason for different behavior of various GCM/RCM. Furthermore we can notice that generally the future performance of the indicators is supporting the detailed statistics and they performing more "dry" effects, indeed. In fact the the flooding is significantly reduced, while the water deficit increase even for a magnitude of difference.

The natural climate conditions are changed, thus the operation of the system is changed. Even though we start with same initial conditions as 2007, big changes of the system behavior are expected. For this reason we can not be satisfied with the optimal point of the "historical" weight combination. Consequently those combinations can be improve if we observe more points, more weight combinations. The goal of this experiment is to see the sensitivity of the indicators and to reconstruct the future Lake Operator range of operating.

Considering the fact that the computing time of one point of the pareto frontier is around 5-6 hours operating time, we are forced to choose few scenarios and run the models only for those, trying to exploit the boundaries of the CC scenarios performance. Therefore we choose 3 different scenarios, guided by different reasons.

IPSL RCA4, RCP45 The first chosen scenario, is located down left in the Pareto scatter plot(4.33). This scenario is showing relatively high water deficit, but it significantly reduces the floods. In reference, it does not give us extreme case, regarding the indicators behavior. However, according the statistics given in section 4.2, this scenario is the driest among all RCP45s and it is one of the hottest. In relation it relatively gives small number of dry spells and heatwaves, hence it does not give the worst indicator's outputs.

Having in mind the last mention the aim is to explore the weights and realize what

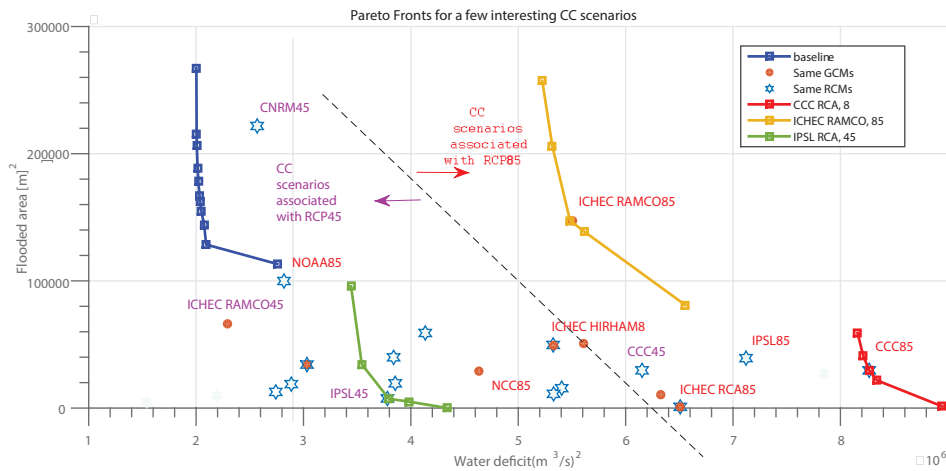


FIGURE 4.34: Pareto Fronts for three interesting CC scenarios

is the reason for this relatively contradicting statements. From fig.?? we can see that the sensitivity of the weights variation is not so high, but still there is room for water deficit improvement, if required. The optimal solution does not differ significantly in the water deficit values but have high range of change related to the flooding.

For this scenario and the ones that give less flooding area than the baseline, should be delivered the opportunity of giving more favor to the downstream agriculture, instead. This means that the DM might decide that the solution should be more weight tuned towards the water deficit giving a higher revenue to the farmers, making it reasonable for the upstream lake shore dwellers. Anyway this depends of plenty socio economics factor, which uncertainty accompanied with the CC and natural uncertainty might change significantly.

CCC 85 This scenario is simply chosen for two reasonable facts: First that in fig.4.34, it gives the extreme water deficit, located down right. Second is the extreme statistical results, like second driest one, after IPSL RCP85 and the hottest one. So its indicator performance is expected.

The uncertainty of this scenario behavior can be visually quantified if we only follow the change of the weight combinations. It is noticeable that this scenario is quite sensitive towards the flooding, in a sense that small change of the weight associated with the floods strongly influence the same indicator.

ICHEC RAMCO22, RCP85 The third CC scenario gives the worst aggregated indicator and, alarming worst location on the plot, right in the middle. The important issue is that it shows significantly worse performance for the both indicators, regarding the baseline performance. Additionally it performs long dry spells and heatwaves (check plot 4.13 and 4.13) in the simulation horizon. This scenario in fact is higher resolution than the previous ones and in fact it gives lower mean temperature and precipitation defining it as an "average" scenario.

Moving along the Pareto frontier, it can be noticed that the behavior is slightly different than the previous ones. In fact here the operator might be more favored towards the water deficit, hence it is less pitched towards the flood weight site. Also the range of the water deficit variation is relatively small moving through the extreme cases ($w_{flood}=1$ and $w_{irr}=0$). Moreover here we have a totally opposite situation than the previous one. If this scenario would project in the future, the lake stakeholders should noticeably concern about the situation. In the same time the farmers would have significant problems with the low water release.

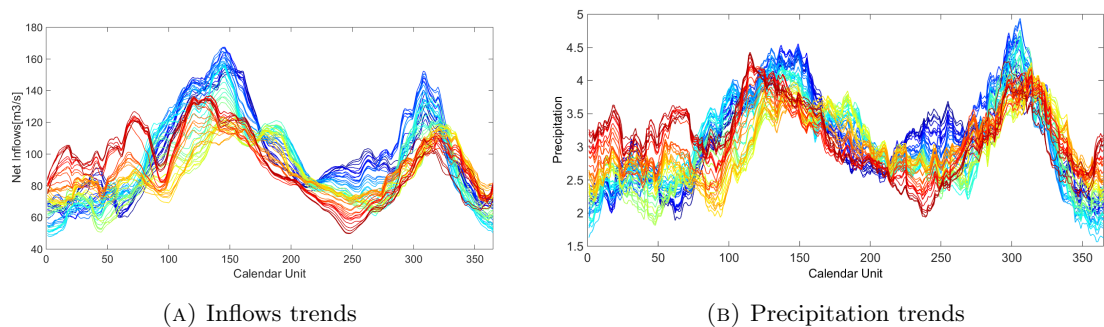


FIGURE 4.35: ICHEC RAMCO rcp85, MASH inflow and precipitation trend representation, $w=10$ days, $Y=25$ years

According to some previous studies this is the most often scenario, hence it is expected to deal with extreme events. Practically here we face winter or late autumn high water levels, when the water is not required from the farmers and dry sultry days in summer where the lake is lower than the natural threshold. This is visible from fig. 4.35, where we have shifting and flattening of the winter peak precipitation, remapped in the inflow MASH with a certain lag. General trend of inflow decrease is quite visible (blue to red, represent moving from present to future). This can not be known from this study (beside the MASH analysis), since our indicators are focused for a holistic preview of the situation.

In the end we can conclude that every scenario has unique behavior and we can not give a global advice for the optimal solutions, in order to asses the future situation knowing the Pareto frontier only of one scenario. The uncertainty is high and its quantifying requires detailed analysis for each scenario, separately. Than a global conclusion is possible or even developing a multiple scenario behavior.

Chapter 5

DISCUSSION and CONCLUSIONS

5.1 Discussion of the results

This dissertation represent a comprehensive analysis and uncertainty quantification of the Climate Change Impact on the water resources management of a quite complex and over exploited system.

The proposed procedure starts with *downloading* of the GCM outputs, from the recently updated EUROCORDEX regional framework, than continues with *statistical downscaling* of the scenarios, in order to derive them to a basin or district level. Two climate variables are considered, *surface mean temperature and precipitation*, which were used for producing catchment discharges trough the *HBV hydrological model* simulations. Thus, the final outputs of the simulation are production of performance indicators or objective functions of the optimization procedure, run by the SDP algorithms. Here arises one of the major perspectives of this study, the *multi-objective* approach, that is preserved trough all the simulations. The entire procedure of analyzing future projection starts with baseline simulation and than followed by testing of the new approaches, e.g. the re-optimization, future scenarios simulations considering the same trades off as the baseline, and the co adaptation.

The investigation starts with some general *statistical analysis of CC* scenarios, covering the entire available horizon. This allows the reader to discover and more objectively

to characterize the future scenarios and develop a hypothesis of a possible scenarios impacts, regarding our study site. The proposed statistics starts by showing the mean temperature and total precipitation during the irrigation period, comparing with the current conditions. This enable us to perceive the magnitude of alteration in the projected future scenarios with respect to the baseline climate. This is like a warning before the reader continue learning the changes. After the general analysis we offer more specific statistic, concentrated on the agricultural district , in order to verify the natural variability and the more accurate information from the high resolution models, i.e. EU11. In reference, the graph suggests that, even though the *lower resolution(EU44) scenarios project the worst average future conditions, some circulation EU11 models* ,like ICHEC, in fact they forecast more extreme events like heatwaves and dry spells that can seriously affect the plant growth. The later give even more comprehensive information for the CC behavior.

Nevertheless, the climate variables information is not enough to disclose a scientific opinion for the CC impact on the considered water system. Apart from direct impact on the agriculture practices, the extreme future climate scenarios may also contribute to the variability of inflow which therefore need to be considered, particularly for the water system we are investigating. Thus, the climate change variables are used to produce an areal inflows from a rainfall-runoff model. Here we are facing the *second source of modeling uncertainty*(the first was obviously the one developed by the CC models). It is also noticed that, some GCM/RCMs show some unrealistic sequences like zero daily inflows in the catchment when dry spell occur.

Having this hydrological projected data we seize the opportunity of using the lake regulation model and the farmers district model in order to asses the impact of the CC on the water related activities in the region. We do expect a dramatic change of the future system performance, given in front the likelihood of more extreme events that are persistently shown in our statistical analysis of future scenarios. The first simulation of the scenarios, following the experiment directions is based on the so called historical trade off ($w_{irr}=0.025$ and $w_{flood}= 0.975$). The first conclusion is that the he projected future scenario shows *prolonged drought seasons* and lack of irrigation water is more than obvious. In addition, most of the CC scenarios show a *reduction in the flooded area* in general, despite ICHEC RAMCO and CNRM that for the same weights register bigger floods than the baseline. Generally the re optimization of the management polices is not enough to overcome the stress conditions due to the deteriorated water availability .

However the objectives performance is not entirely unacceptable for all the scenarios. In fact some "hot" scenarios like NCC and IPSL show quite good performance in comparison.

Here arises the another effect of the uncertainty, or more precise here we clearly notice the impact of the *intrinsic uncertainty*. Furthermore the uncertainty significantly affects the results. We analyzed the inner variability and the *structural uncertainty* in details. The previous statement strongly suggests that, even though, according all previous studies the modeling structural uncertainty is predominant, the natural or *inner variability is not negligible*, especially if we consider short horizons. This uncertainty can be reduced if we explore more horizons and consider a sliding horizon trough the simulation. Also the initial state assumptions and lack of some meteorological data influence this uncertainty.

The third one is an *uncertainty related with the modeling and decision maker knowledge*. For the former we defined an experiment that squeezed the analysis for both RCMs and GCMs. The final results suggests that the scenarios related with same GCM show less uncertainty and vary in a smaller range regarding the indicators. on the opposite the experiment dedicated to the scenarios with same RCMs, constructed very disperse picture. The optimal points, related with the mentioned weights vary form relatively acceptable water deficit(NCC) towards extreme behavior (CCC85), as well as for the flooding, where CNRM RCA deliver a huge floods, while IPSL, ICHEC RCA RCP45 flooding is almost negligible. The final conclusion is that we are going to stick to the global CC scenarios literature reviews (see Chapter 3, section3.2) and assign the highest uncertainty to the GCMs. This is not unexpected since the institute's modeling procedure and approaches differs a lot one from another. In summary the dispersion of the GCMs is quite high, and cover wide range of the indicators performance. While RCMs are enveloped in the smaller indicators area and it can be noticed that the added value after the dynamical downscaling is not weighty as the global climate modeling structure. In addition to this experiment we run an optimization of the lake regulation policy with consistency of the *feedback loop*, and explore the behavior of few weight combinations, trying to define a future management policy. The main purpose was not finding a best solution, but more see the possible change of the current lake operation and discuss the operating uncertainty. The lake operating uncertainty was quantified on a similar way as the *baseline re-optimization*. Accordingly, the future projected trade offs highlight that more attention has to be paid towards adaptation of the weights associated with

the irrigation deficit. In other words the operator should give a pecking order to the irrigation, meaning more reliable feedback or even adopting an on line demand police. On contrary in the baseline scenario, the operator uncertainty was based on the *natural variability*, current hydrological condition and lake level(state), thus the operator was more confident if she gives a favor to the floods events. This is confirmed after checking the farmers profit, where the variation is not that weighty ,even between the marginal optimal points of the Pareto.

In fact after the re-optimization of the baseline management policy there was significant improvement of the indicators performance, especially the water deficit. Having farmer's water demand feedback is more than necessary, which requires involvement of farmer's decision making participation, and is expected to achieve more benefit in reality. The last might even suggest on demand policy creation, which would affect with better policy as well as with faster and easier modeling, since it automatically decrease the computational time.

In order to explore the potential adaptive strategies for mitigating the negative climate change impact, a simple *co adaptation* measure was integrated in the optimization model. Adding the *crop rotation* as a planning action resulted with improvement of there optimized management policy and a higher revenue of the farmers. The last was implemented, due to the fact that the future CC impact is seriously threatening, and this kind of even simple measures can improve the water allocation in any system.

5.2 Suggested future improvement and incoming challenges

Firstly we refer to the natural variability influence,where it is suggested improvement with use of longer horizons, accompanied with backcast assessment and comparison with the baseline and more recent years of simulation. In order to distinguish between natural variability and Climate Change,use of longer observed historical time-series are preferable for constructing more comprehensive analysis, extended for near future, e.g the following 20 years.In order to have more unique results the length of the horizon should be definitely longer than 10 years. After the robust analysis of the EUROCORDEX framework, it is preferred to develop a multiple model scenarios,where the models would cover their own anomalies by combining among. This should not be naive procedure of random combinations,but more a detailed investigations of the model structures and

their effects on the environment, in general. It should end up with a better representation of the CC and inner variability.

Plenty of assumptions were made especially considering the water prices and crop market, as well as for some meteorological data. This can be achieved by developing economic models for water prices and crop market price, even though it still abstract to define a certain socio-economic scenario. Thus multiple scenarios with combinations of more meteorological data, accompanied with possible future planning actions like dam constructions, change of irrigation techniques, are strongly suggested for future researches in this field.

Furthermore improvement of the hydrological model and assessing the influence of the old one is another issue that might be discussed. I.e. assessment of the HBV model can be done if a comparison between CORDEX back-cast and historical inflow data is performed. The improvement stands for better representation of the dry days and including the glacier dynamics, as well as ground water influence of the water bodies current state. Due to the modeling errors, a scientific effort towards inventing new methods for assessing the modeling uncertainty, structural and parametric. The later also suggests, that a more recent calibration of the models is required, using the last available data upgrades, meaning that the future simulation would be less uncertain if the models are "updated". This trace us back to the socio-economic uncertainty, since the model outputs are used as indicators used for the optimization process. In fact the modeling can be improved, but we can hardly speak even for broad uncertainty reduction in the decision making processes. The political influence is very delicate as well as stakeholders behavior and it is unlikely to assess their future impact.

The modeling errors, that are induced because of the scale mismatch can not be significantly improved, since those error are unavoidable (beside a detailed CC model is developed for specific area), even it is suggested different methods than QQ to be performed and compare the difference. In the end even, an increasing of the complexity and accuracy of the simulation model is performed to improve the trustability of the results, it is still a question if it would be sufficient to compensate for the large uncertainty that affects the assessment analysis. And for the uncertainty of the DMs and stakeholders it is suggested their active participation in this kind of studies and willingness to contribute as a part of more advance social models in order to descriptively quantify their uncertain behavior, at least.

In the end, it superficial if we say nothing about the improvement of the existing model.

Therefore, beside of the improvement of the model computational performances, it should be considered involvement of more stakeholders in the entire procedure. This specifically is aimed towards the preserving the environment and the ecosystems, of such complex and exploited system. Therefore including the "environmental" issues and the stakeholders representing them, means developing a new performance indicator that will summarize their interests and criteria. This will lead to increasing of the multi-objective space and inducing new challenge for new researches.

5.3 Final words

This study is concentrated on robust assessment of the CC scenarios and their impact to the water resources management. Additionally there are some suggestions for improvement and mitigation of the negative CC impacts. Even though the results are quite interesting, the conclusions are not exclusive, given the other uncertainty source that are not taken into account in this case. The goal of this dissertation is only to deliver an information about the climate change influence on the agriculture and water resources allocation. It is a nutshell of the newest climate change data and their performance in this complicated water supply scheme. The offered output information should be more considered for a present development of new strategies and changing habits, as well as, increasing of the awareness of all the included stakeholders. Also, it is counterargument to those who exaggerate the climate change and give a higher weight than it is. After all, this work is trumpet call for change, change to deal with the uncertainty, change to save the fresh water, save the planet from the "thirsty days".

Appendix A

Stochastic Dynamic Programming

In the field of mathematical optimization, stochastic programming is a framework for modeling optimization problems that involve uncertainty. Whereas deterministic optimization problems are formulated with known parameters, real world problems almost invariably include some parameters. When the parameters are known only within certain bounds, one approach to tackling such problems is called robust optimization. Here the aim is to find a solution which is feasible for all such data and optimal in some sense. Stochastic programming models are similar in style but take advantage of the fact that probability distributions governing the data, the disturbances are known or can be estimated. The goal here is to find some policy that is feasible for all (or almost all) the possible data instances and maximizes/minimizes the expectation of our objective function of the decisions and the random variables. More generally, such models are formulated, solved analytically or numerically, and analyzed in order to provide useful information to a decision-maker.

It was anticipated above that we are dealing with off line policies and the solution of our Design problem will be performed by the meanings of SDP. However, considering all the types of policies we will present small review about the offered solution regarding on line and off line polices. Having the policy p as a succession of laws in order to determine the optimal policy p^* requires infinite number of values to be determined, therefore defining the optimal policy is physically impossible. As a particular case we assume that the policy is finite for every t , has a finite number of elements, and the model will be assumed as automaton. If this is not satisfied than approximation has

to be considered. This model is called discretized model or system, in fact this one approximates the original natural system, so the optimization algorithms can be applied. The point is to define a rectangular set of states, controls and disturbances has to be defined, than the discretized model is denoted with the following expression:

$$\hat{x}_{t+1} = \hat{f}(\hat{x}_t, \hat{u}_t, \hat{\varepsilon}_{t+1}, \hat{w}_t), u^p \quad (\text{A.1})$$

where $\hat{x}_t \in \hat{S}(x_t), \hat{u}_t \in \hat{S}(u_t), \hat{\varepsilon}_{t+1} \in \hat{S}(\varepsilon_{t+1})$, for $t=0, \dots, T-1$, and $u^p \in U^p$.

The classification of the approaches to the solutions is firstly on non-learning based and learning based approaches. Non learning off line PV polices are related with the functional and the parameter design approach.

The functional design assumes system automaton, i.e system that in each time step the state can only assume finite number of values. If we deal with infinite number we must set an approximation for that, or discretization. Therefore the optimal policy is determined as a succession of laws, upon which no conditions are imposed; in other words in the space of all the functions the best ones are looked for. The optimal policy can be determined only when the states, controls and disturbances that act upon are finite or periodic.

Another approach is the *parametric* one. It assumes a class of functions to which the control law must belong and it is fixed a priori. Practically each function is defined by finite number of parameters, thus the policy is defined by finite number of parameters. The point is actually identifying parameters that minimize the objective.

Above mentioned approaches assume that there is available information that will define the environment of the model. This experiment approved that this procedure is quite time consuming, and requires computational effort. Furthermore any error or assumption that is pre-processed in the model is mirrored in quality of the design policy. In other words we have to have so called nominal scenarios in order to use the off line approaches. However in the reality is not like that, in fact there a plenty of discrepancies that criticize this approach. I.e the irrigation season is late, or the hydropower plant is under maintenance, but the operator behavior is already predefined so we might have unexpected events like floods or less water for the irrigation[26]. The answer is to re-design on-line adaptive policy or control. It has to be clarified that using off line policies and developing super effective models ,and therefore decreasing the uncertainty problem of the nature is possible, but is exhaustive and in computational terms the

”segmentation of the optimization will fault”, since the PC has to run infinite time. In order to reduce the states of the model, the online policy is introduced. So here we deal with Complete problem (off line not practically solvable) and Reduced problem (on line as way to solve). In simple words the On line policy is solving the same problem (check Chapter 3 defined in off line policy at time t, i.e applying the designed control in same time, producing a control u that is the solution of the following optimal problem. However, here we will deal only with off line policy and only the functional approach will be explained. In order to start the description of this approach we should introduce few general definitions and characteristics.

Firstly as in chapter 2 we define \mathbf{x}_t as state and \mathbf{u}_t as control at each stage. Specifically this programming will be used for two purposes: solving the distributed parameter optimization problem for each agent separately (check MAS, Appendix ??), and solving the lake regulation policy considering the two objective functions (eq.3.5 and eq.3.6). In order to explain the SDP process we will recall the lake regulation policy and one optimization function, having in mind that similar stands for the second one. As it was defined up the indicator value is also called step cost, since the design indicator is considering h functions in the horizon H. Also we know the representation of the water deficit objective function and we can say that it depends of the control u_t and the state \mathbf{x}_t , thus the volume s_t . When considering SDP we have to weigh the immediate cost $g_t = (x_t, u_t, \varepsilon_t + 1)$, that will be incurred in the next state $\mathbf{x}_t + 1$, or adopting the optimal decisions in the following stages. That cost is determined as $H^*_{t+1}(\mathbf{x}_t + 1)$ and it is called *optimal cost to go*. If known H^*_{t+1} the decision m_t can be delivered by optimizing (in our case minimizing the deficit and the flooded area) the sum of the immediate cost and cost to go with respect to u_t :

$$m_t^*(\mathbf{x}_t) = \arg \min_{\mathbf{u}_t \in \mathcal{U}_t(\mathbf{x}_t)} E_{\varepsilon_{t+1} \sim \phi_t(\cdot)} [g_t(\mathbf{x}_t, \mathbf{u}_t, \varepsilon_{t+1}) + H^*_{t+1}(x_{t+1})] \quad (\text{A.2})$$

where \mathbf{x}_{t+1} is computed with equation (??). Therefore, as visible in equation (A.2), the optimal cost-to-go $H_t^*(\mathbf{x}_t)$ associated to the current state can be found by knowing the one at time $t + 1$ and specifically will be given by the following equation, the so-called Bellman equation (Bellman, 1957, 1962).

$$H_t^*(\mathbf{x}_t) = \min_{\mathbf{u}_t \in \mathcal{U}_t(\mathbf{x}_t)} E_{\varepsilon_{t+1} \sim \phi_t(\cdot)} [g_t(\mathbf{x}_t, \mathbf{u}_t, \varepsilon_{t+1}) + H^*_{t+1}(x_{t+1})] \quad (\text{A.3})$$

Hence, this equation can be used to determine the costs-to-go and thus the optimal actions in each state by proceeding backwards from the final stage (time instant) to the initial one, as the SDP algorithm actually does. This function is known as Bellman equation (in our case $H(x_t, u_t)$), and provides the optimal cost to go at time t , given one at $t+1$. It is clear that the core of the SDPs is this equation proceeding it in recursive way, moving backwards from the final stage. In general the Bellman Principle of optimality states that the decision u_t can be optimal if and only if every decision is optimal at its stage. If we try to explain the eq.?? in a given sequence we can say that the optimal policy is perfectly known if H^* is known, and H^* is known if we have perfect state information (the model give a perfect output for the states x_t).

Before the formulization of the problem is done we would recall the eq.

$$H_0^*(x_0) = \min_p E_{\{\varepsilon_t\}_{t=1,\dots,h}} \left[\sum_{t=0}^{h-1} g_t(\mathbf{x}_t, \mathbf{u}_t, \varepsilon_{t+1}) + g_h(x_h) \right] \quad (\text{A.4a})$$

subject to

$$\mathbf{x}_{t+1} = f_t(\mathbf{x}_t, \mathbf{u}_t, \varepsilon_{t+1}) \quad t=0,1,\dots,h-1 \quad (\text{A.4b})$$

$$m_t(\mathbf{x}_t) \triangleq \mathbf{u}_t \in \mathcal{U}_t(\mathbf{x}_t) \quad t=0,1,\dots,h-1 \quad (\text{A.4c})$$

$$\varepsilon_{t+1} \sim \phi_t(\cdot) \quad t=0,1,\dots,h-1 \quad (\text{A.4d})$$

$$\mathbf{x}_0 \text{ given} \quad (\text{A.4e})$$

$$p \triangleq \{m_t(\cdot); t = 0, 1, \dots, h-1\} \quad (\text{A.4f})$$

$$\text{any other constraints } t=0,1,\dots,h-1 \quad (\text{A.4g})$$

With the Stochastic Optimal Control Problem formulated in this way, the SDP algorithm can be applied to find the optimal solution. Since the assumption on the basis of the whole optimization procedure described in Chapter ?? is that farmers and lake Regulators carry out the planning of, respectively, crop production activities and reservoir regulation policy at the beginning of each year, the SDP algorithm will be used in its finite-horizon formulation. Thus, the indicator has the following form

$$\mathbf{i} = \sum_{t=0}^{h-1} g_t(\mathbf{x}_t, \mathbf{u}^p, \mathbf{u}_t, \mathbf{w}_t, \varepsilon_{t+1}) + g_h(\mathbf{x}_h, \mathbf{u}^p) \quad (\text{A.5})$$

Furthermore there are several algorithms that solve SDPs problem and they are related with the horizon, i.e. for infinite horizon TDC(Total Discounted cost) can be considered. For finite horizon the problem can be defined with the following equations:

Step 0 - Initialization: *Let*

$$H_h^*(\mathbf{x}_h) = g_h(\mathbf{x}_h), \forall \mathbf{x}_h \in \mathcal{S}_{\mathbf{x}_h} \quad (\text{A.6})$$

Step 1: *For $t = h - 1, h - 2, \dots, 1$, compute the costs-to-go $H_t^*(\cdot)$ with the following recursive equation*

$$H_t^*(\mathbf{x}_t) = \min_{\mathbf{u}_t} E_{\varepsilon_{t+1}} [g_t(\mathbf{x}_t, \mathbf{u}_t, \varepsilon_{t+1}) + H_{t+1}^*(\mathbf{x}_{t+1})], \forall \mathbf{x}_t \in \mathcal{S}_{\mathbf{x}_t} \quad (\text{A.7a})$$

subject to

$$\mathbf{x}_{t+1} = f_t(\mathbf{x}_t, \mathbf{u}_t, \varepsilon_{t+1}) \quad (\text{A.7b})$$

$$\mathbf{u}_t \in \mathcal{U}_t(\mathbf{x}_t) \quad (\text{A.7c})$$

$$\varepsilon_{t+1} \sim \phi_t(\cdot) \quad (\text{A.7d})$$

$$\text{any other constraints relative to } [t, t+1) \quad (\text{A.7e})$$

Step 2 - Termination Test: *Given $t = 0$, compute $H_0^*(\mathbf{x}_0)$ with equation (A.7a) for \mathbf{x}_0 . The value obtained is the optimal J^* of the objective of problem (??), and the h functions $H_t^*(\cdot)$ computed individuate the Bellman function $H^*(\cdot)$ of the Problem.*

The optimal policy p^* is thus defined by equation A.2, in which the values $H_{t+1}^*(\mathbf{x}_{t+1})$, for $t = 0, \dots, h - 1$, are provided by the h functions $H_{t+1}^*(\cdot)$ obtained in Steps 0 and 1, which are time slices of the Bellman equation.

It can be observe that from the equation A.3 the bellman function is computed, and since our system is automaton (discretized, finite) it is described by $(\mathbf{u}_t, \mathbf{x}_t)$ at each state. Therefore a double entrance table that associate with this table is formed and in fact present the optimal cost to go H^* associated with every step. If the disturbance is

not change, the controls might be stored and the bellman function does not need to be computed again for the next state computations. I.e. we have constant normative water demand, it is enough to compute the Bellman function just the first simulation year, than save it and continue with the horizon. By these means the historical point of the pareto is determined, associated with the weights It is worthy to be mention the complexity of the SDPs and the so called curse of dimensionality, which strongly limits the number of state variables that can be used to model the water system, even when adopting the most advanced approaches, e.g. coarse grid approximation or neurodynamic programming (for a review of such approaches, see, for example, Castelletti et al., 2007; 2008b, and references therein). One of the SDP algorithms was presented above in order to solve our Control Problem, however the experience and the real use of it in order to perform the results was time consuming and very robust. The robustness come from the assumptions made, like separability of the indicators, deterministic disturbance (or white process). As it is case now the solution requires precise solution, thus As we know, in order to determine the function $H(\bullet)$ with the SDP, the state set Sx_t must be a discrete and finite set at every instant t . Suppose, for example, that every state component can assume 100 values at every instant: the set Sx_t will contain $100n_x$ points. For each of these points minimization must be carried out numerically with respect to the control u_t . This is performed with a minimum search algorithm in $U_t(x_t)$, which is a set in the space Rn_u . For every value of $u_t \in U_t(x_t)$ one must evaluate the corresponding expected cost-to-go; this leads to the computation of the expected value and thus requires a numerical integration in the space Rn_ε . All this proves very onerous, from the viewpoints both of computing time and of memory occupation. It follows that the algorithms of the SDP can, in fact, only be applied when the dimensions n_x , n_u and n_ε are very small. To deal with Problems in which the dimensionality of the system is higher, it is necessary to have recourse to alternative strategies (AC, RSS 2007a). Meta modeling is one descent suggestive framework in order to decrease the states, another is Linear Quadratic Gaussian and few others (see). Also in order to tackle this "curse of dimensionality", there are several types of methods have been studied. i) Method based on aggregation and decomposition. A method was proposed in which the control problem for a system of M reservoirs in series was decomposed into M sub-problems each with two reservoirs: one a reservoir from the original problem and the other an aggregate representation of the reservoirs downstream of that reservoir. The solution time increases linearly with the number of reservoirs in

the system and so the approach is practical for large systems. This method was extended to a model consisting of that reservoir and a two-dimensional representation of the rest of the system. A Benders decomposition algorithm was proposed and applied it to systems including 37 reservoir. ii) Method based on approximate of utilization function. An approach based on efficient discretization of the state space and approximation of the value functions was proposed over the continuous state space by means of a flexible feed forward neural network. This method can be used for nonlinear objective function and has been applied to multi-reservoir systems with 30 reservoirs. iii) Method based on Stochastic Dual Dynamic Programming (SDDP). A sampled hyper plane was used to provide an outer approximation of the benefit-to-go function. These hyper planes are equivalent to Benders cuts in Benders decomposition. An interval-parameter multistage stochastic programming method was proposed for supporting water re-sources decision making, where uncertainties expressed as random variables and interval numbers could be reflected. This method was improved that handles uncertainties through constructing a set of scenarios that is representative for the universe of possible outcomes, as well as reflects dynamic features of the system conditions and risk levels of violating system constraints within a multistage context . They also recognized that it was a challenge to extend this method to flood control operation of reservoir due to large scenarios(Liu et al. 2012).

Appendix B

Multi Agent Based Systems

In chapter 3 we have explained the pure planning problem and procedure of solving the Design problem. In fact our crop model assumes pure deterministic planning, since no management decisions are taken. However the solution is not straight forward. We have to deal with 66 farmers as a separate DMs. In this section we present the Multi agent decision making (MADM).

B.1 Brief Introduction Into the Concept

Artificial Intelligence (AI) has emphasized building stand-alone systems that can solve problems with minimal help from other systems (computer or human). A more powerful extensible strategy for overcoming the inherent bounds of intelligence present in any definite AI or natural system is to put the system in a society of systems so that it can draw on a diverse collection of expertise and capabilities in the same way that people overcome the limitations of individuals by banding together into societies that are designed to accomplish what individuals cannot. The ability to flexibly team up and coordinate group activities toward individual and collective goals is a hallmark of intelligence.(Durfee and Arbor n.d.)

DAI community started forming in the early 1980s when the complexity of AI problems exceeds the capabilities (i.e., knowledge, computing resources, and perspective) of a single entity (agent). Particularly complex, large, or unpredictable problems require indeed to develop multiple, specialized, and modular components (agents), which are

also able to interoperate via techniques based on negotiation or cooperation (O’Hare and Jennings, 1996; Jennings et al., 1998). The DAI research field is related with more specific fields: Parallel Artificial Intelligence (PAI), Distributed Problem Solving (DPS) and Multi-Agent Systems (MAS). The theory of multi-agent system (MAS) has emerged from a sub-field of researchers in artificial intelligence (AI), called distributed artificial intelligence (DAI). The bounds of Distributed Problem Solving (DPS) and Multi-Agent Systems (MAS) are not well defined. Both are composed by a group of entities that interact. One may consider that in a DPS system, all the entities work together with a common interest of solving a well-defined problem, unlike the entities of a MAS that may have diverging interests (“Di S Tribute D ARTificIal IntELLigENCE” 2011)[27]. However, not all systems composed by agents could be considered DPS systems. The example of economic agents or a system composed by agents that simulate a soccer game are not DPS systems at all. In this kind of systems, the single agents have their own interests and they might cooperate or compete, agree or disagree, etc. Almost all kind of social interactions may exist in this context. So, a new research field called “Multi agent Systems” arose (“Di s tribut e d Artificial Intellig e n ce,” 2011,Anonn)[27].

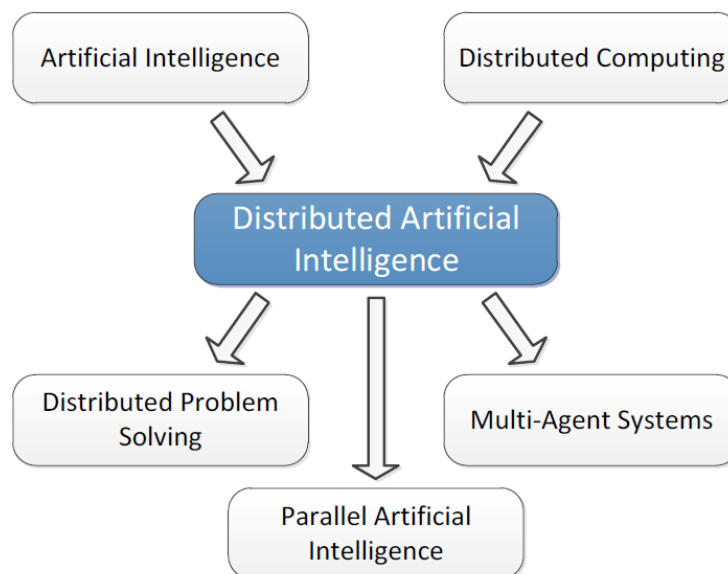


FIGURE B.1: Distributed AI).

The following statement given by Boulbanau[28], has purpose to reduce the variety of different opinions about ABS and make it less ambiguous in the further explanation of our certain case.” ABS is a mindset more than a technology. The ABM mindset consists of describing a system from the perspective of its constituent units. A number of researchers think that the alternative to ABS is traditional differential equation modeling;

this is wrong, as a set of differential equations, each describing the dynamics of one of the system's constituent units, is an agent-based model. A synonym of ABS would be microscopic modeling, and an alternative would be macroscopic modeling." Depending on the characteristics of the environment, the specific structure of the agents as well as the methods defining their behaviors can be different. Russell and Norvig (1995) suggest four major distinguishing properties for characterizing MAS environments:

- **Deterministic or stochastic:** an environment is deterministic if any action has a guaranteed outcome, and stochastic if there is uncertainty on the effects of the action;
- **Static or dynamic:** a static environment can be assumed to remain unchanged (except by the effects of agents actions), while a dynamic environment is characterized by multiple processes evolving in time and beyond agents control;
- **Accessible or inaccessible:** an environment is accessible if each agent can obtain complete, accurate, and up-to-date information about the environment state, and inaccessible otherwise.

The term agent is used to denote a hardware or software system that is:

Autonomous – it operates without the direct intervention of others;

Social – it interacts with other agents using an agent-communication language;

Reactive – it perceives its environment and responds to changes in it; and

Proactive – it is able to exhibit goal-directed behavior.

Multi-Agent Systems comprise multiple agents, which interact among themselves or with objects in their environment. Purely reactive agents act using a stimulus-response type of behavior and respond to the present state of the environment (Sycara, 1998). They do not look at history or plan their strategy over the future. This characteristic allows the design of simple "if-then" agent's behaviors. Yet, they make decisions based on local information only and do not predict the effect of their decisions on global behavior. This myopic behaviors can lead to unpredictable and unstable system situations (Thomas and Sycara, 1998).

B.2 Environmental terms

Multi Agent-based simulation (MABS) is being used in environmental modelling for many reasons that have already been discussed in the literature (e.g. Bousquet and Le Page, 2004; Ferber, 1999; Judson, 1994; Taylor and Jefferson, 1994). MABS provides a framework in which tractable techniques can be implemented that meet various requirements of environmental management modeling. First of all, MABS permits the coupling of environmental models to the social systems that are embedded in them, such that the roles of social interaction and adaptive, disaggregated (micro-level) human decision-making in environmental management can be modeled. It also permits the study of the interactions between different scales of decision-maker, as well as the investigation of the emergence of adaptive, collective responses to changing environments and environmental management policies. (Hare n.d.). NOTE: The terms MABS, MAS, AMBAS refer multi agent based modeling and simulation, hence this technique suffers from disentangling terminology in the scientific world. In order not to cause confusions most use term will be MAS, although the other will be used, so the reader would not meet a problem with the references. The MABS models selected here focus on current environmental management and/or assessment issues. They are also focused on representing the interactions between human and natural systems, whereby the agents represent some sort of a human entity (individual people, families, or other groups) and the environment with which the agents interact represents some sort of natural resource or landscape. Ecology was the first environmental discipline that adopted MAS approaches due to their similarity with individual-based models (e.g., Huston et al., 1988). The aim of these works is to study the behavior of a population, where the processes involved are modeled at the agent level to take into account the heterogeneity of the individuals (Bousquet et al., 1999). MAS tools are also used to study land use change and agricultural systems (Berger, 2001; Berger and Ringler, 2002; Naivinit et al., 2010; Schreinemachers and Berger, 2011; Le et al., 2012; Ralha et al., 2013) according to the "representative independent farm approach" (Hanf, 1989), which consists of a number of independent farm models added up to compose a sector result. Agent-based models are used to represent human landscape systems where a set of human agents interact with each other and with the environment. Problems in water management are exacerbated by unsustainable development, climate change and the uncontrolled growth of the world population. The primary purpose of water resources management is, thus, to assure and

improve the allocation of water, preserve its quality, cope with extreme events (such as floods), mitigate droughts, and manage the inter-annual variability of water supply, especially in the Mediterranean Area. In all the above cases, ensuring communication and exchange of information and knowledge is a decisive factor for providing enduring and socially approvable solutions. That is exactly why the participatory approach is becoming a pre requisite to every legislative or planning process dealing with Integrated Water Resources Management (IWRM). According to GWP public participation (PP) requires that stakeholders at all levels of the social structure have an impact on decisions at different levels of water management, thus fostering the adoption of more decentralized and cooperative approaches that take into account all processes involved in human-influenced ecosystems. Evident is the need for Decision Support Systems (DSS) that integrate the ecological and socio-economic dimensions of water management. Agent-Based Modeling and Simulation (ABMS) techniques due to their inherent characteristics can be effectively used to model both the ecosystem dynamics and the complexity of natural resource management. Appendix ? Offers a list of different case studies where the MAS was implemented in relation with Water Resources Management. Problems in water management are exacerbated by unsustainable development, climate change and the uncontrolled growth of the world population. The primary purpose of water resources management is, thus, to assure and improve the allocation of water, preserve its quality, cope with extreme events (such as floods), mitigate droughts, and manage the inter-annual variability of water supply, especially in the Mediterranean Area. In all the above cases, ensuring communication and exchange of information and knowledge is a decisive factor for providing enduring and socially approvable solutions. That is exactly why the participatory approach is becoming a prerequisite to every legislative or planning process dealing with Integrated Water Resources Management (IWRM). According to GWP public participation (PP) requires "that stakeholders at all levels of the social structure have an impact on decisions at different levels of water management", thus fostering the adoption of more decentralized and cooperative approaches that take into account all processes involved in human-influenced ecosystems. Evident is the need for Decision Support Systems (DSS) that integrate the ecological and socio-economic dimensions of water management. Multi Agent-Based Modeling and Simulation (MABMS) techniques due to their inherent characteristics can be effectively used to model both the ecosystem dynamics and the complexity of natural resource management (Series 2004, UK). It is worthy to mention that in the water resources field, the

first contribution adopting proactive MAS was presented in Yang et al. (2009), where the multiple distributed water users are modeled as self-interested agents acting in a distributed decision process to solve a water allocation problem. After reviewing the papers and the list of studies done we could state that MAS are used to estimate the effects of alternative management policies in order to support decision makers in the water management sector and that they have successfully been used to tackle water management problems, thus, showing a great potential for future DSS (Developing Decision Support Systems) development (EC, noetrum project). The selection of a framework based on MAS naturally allows the representation of multiple decision makers or stakeholders (agents), which act in the same environment, thus influencing each other, and need to coordinate to maximize the system-wide efficiency in the use of the available water. The adoption of this agent-based perspective aims to move beyond the traditional centralized approach to water resources management and to analyze different levels of cooperation (e.g., Watkins, 2006), from fully coordinated strategies and full information exchange to completely uncoordinated practices where all the decision makers independently pursue their local objectives. Finally, in MABM approach, the system is formulated from the perspectives of the individual agents, which are modeled as discrete autonomous entities with particular goals and actions (Ng et al. 2010). In comparison with traditional models, ABMs are flexible, they capture emergent phenomenon, and incorporate real world systems involving complex human decision-making (Bonabeau 2002)[28]. The key steps in developing an agent-based model are (Macal and North 2006a, b):

1. Identifying agents;
2. Accurately specifying their distinct behaviors;
3. Defining the environment the agents live in and interact with;
4. Identifying the agents relationships and develop a theory about their interactions with each other and the environment;
5. Developing essential agent-related data;
6. Appropriately representing agent-to-agent interactions as well as agent-environment interactions;
7. Validating the agent behavior model.

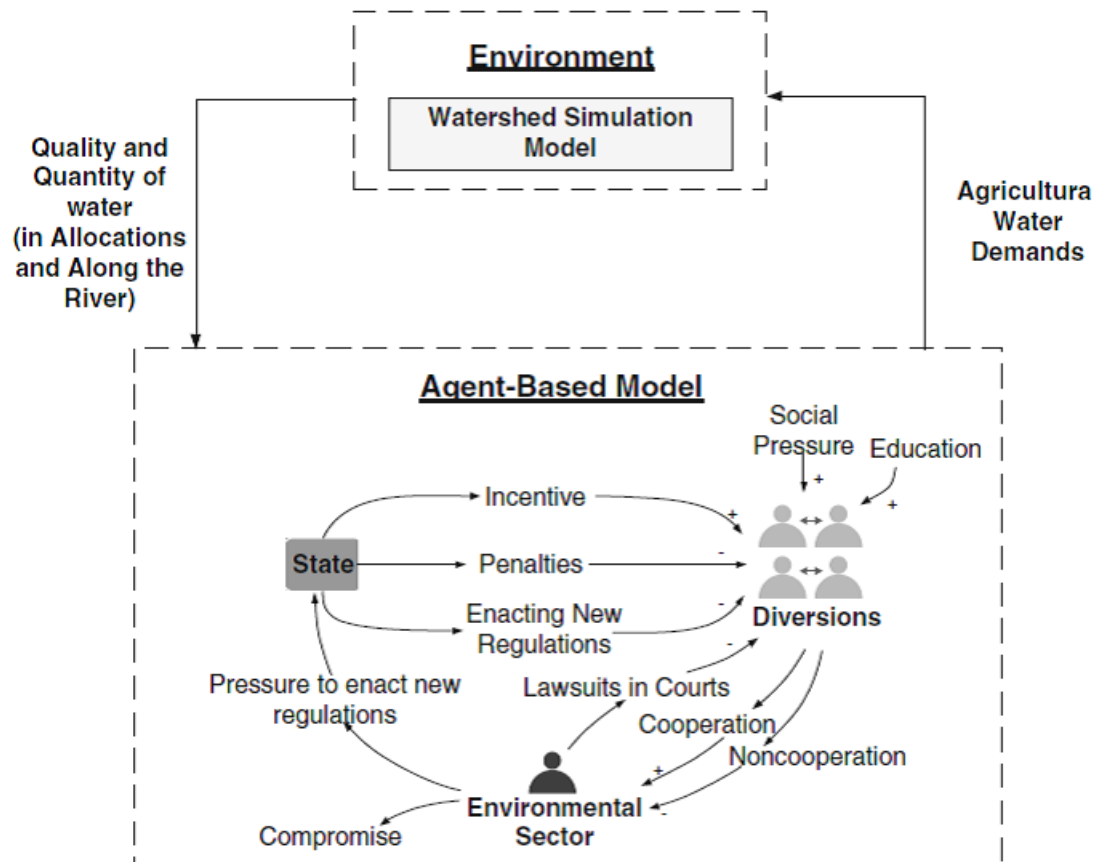


FIGURE B.2: Agents interactions with the environment.

The figure above ?? presents full interaction agent to agent and environment to agent. Different agents has different characteristics. For example the Farmers are reactive agents with rule of behavior in order to maximize their profit, and behave simple according their experience, and the rights in the law.

B.3 MAS for planning problem

In the first section we have seen different studies related with MAS and water resources management. In this section we will introduce some specification regarding our case study, the crop model and Muzza region. This part we will restate the approach suggested by Matteo Guliani and concentrate on the planning problem explained above. According the key principals of MAS and the defined planning problem we can define each agent/farmer as a local problem modeled like:

$$u_i^{p*} = \arg \max_b f(b) \quad (\text{B.1a})$$

subject to

$$c_{i,1}(u_i^p, u_{-i}^{p*}), \dots, c_{i,1}(u_i^p, u_{-i}^{p*}) \leq 0 \quad (\text{B.1b})$$

$$u_i^p \in D_i \quad (\text{B.1c})$$

,where $i = 1, \dots, q$, u_i^p are the decision variables of the i_{th} agent and u_i^p the ones of all the other agents except i . The i_{th} agent's decisions are optimized with respect to its local objective function $J_i(\bullet)$, which however depends also on the decisions of the other agents. It is worth noting that also the constraints in eq.B.1 depend on both the u_i^p and u_{i-1}^p .

In such distributed problems, the agents look at their local objectives only, without considering the potentially negative externalities that their decisions produce for the others. The two main approaches developed within the DAI field for investigating how agents can instead coordinate their decisions are distributed constraint satisfaction problems (DCSPs, see Yokoo and Hirayama (2000))[29] and distributed constraint optimization problems (DCOPs, see Modi et al. (2005)[28]). The DCSP formulation defines a distributed feasibility problem with Boolean constraints, which can be only satisfied or unsatisfied, while the DCOP is a distributed optimization problem dealing with objective functions represented as a weighted sum of costs or valued constraints. According to these formulations, each agent solves a local planning problem with respect to its objective, subject to a set of constraints conditioning its decisions. The constraints represent either physical constraints (e.g., canal capacity) or normative constraints (e.g., minimum environmental flow). The Distributed Constraint Satisfaction (DCSP) paradigm has been proposed as a way to model and reason about the interactions between agent's local decisions. In DCSP each agent controls the value of a variable and agents must coordinate their choice of values so that a global objective function is satisfied. Initially they are developed from CSP (Constrained optimization problem), in a sense that the variables and constraints are distributed among automated agents. Finding a value assignment to variables that satisfies inter-agent constraints can be viewed as achieving coherence or consistency among agents. Achieving coherence or consistency is one of the main research topics in MAS.

B.3.1 Distributed constraint optimization problems

As it was anticipated above our coupled system and the crop model more specifically can be accounted into the general definition of DCOP considering the planning actions, like crop rotation. Therefore briefly we will introduce the structure of DCOP.

The roots of the DCOP, are related with CSP, and therefore DCSP, in the end the issue to be extended towards this method satisfying the principles of MAS.

A DCOP consists of n decision variables, $p^p = [u_1^p, \dots, u_n^p]$, each assigned to a different agent, where the values of the variables are taken from finite, discrete domains D_1, \dots, D_n , and of a number of valued over the values of these variables $c_1(u^p), \dots, c_r(u_i^p)$, where $c_j(u_i^p) \in R$. A solution of a DCOP is an assignment of values to all the variables such that a given objective function g is maximized or minimized[28]. Usually, the objective function is a weighted sum of the functions representing the costs for constraint violations and is minimized, namely: $\min_u \sum w_j \cdot c_j(u^p)$, where w_j is the weight of $c_j(u^p)$. DCOP demands techniques that go beyond existing methods for finding distributed satisfactory solutions and their simple extensions for optimization. A DCOP method for the types of real-world applications previously mentioned must meet three key requirements. First, since the problem is inherently distributed, we require a method where agents can optimize a global function in a distributed fashion using only local communication (communication with neighboring agents). Methods where all agents must Communicate with a single central agent are unacceptable. Second, we require a method that is able to find solutions quickly by allowing agents to operate asynchronously[30, 31]. A synchronous method where an agent sits idle while waiting for a particular message from a particular agent is unacceptable because it is wasting time when it could potentially be doing useful work. Finally, provable quality guarantees on system performance are needed. For example, mission failure by a satellite constellation performing space exploration can result in extraordinary monetary and scientific losses. Thus, we require a method that efficiently finds provably optimal solutions whenever possible and also allows principled solution-quality/computation-time trade-offs when time is limited[32].

A solution strategy that is able to provide quality guarantees, while at the same time meeting the requirements of distributedness and asynchrony. solution strategy that is able to provide quality guarantees, while at the same time meeting the requirements of distributedness and asynchrony, is currently missing from the research literature. A

well-known method for solving DisCSP is the Asynchronous Backtracking (ABT) algorithm of Yokoo, Durfee, Isida, and Kuwabara[10, 28, 29]. Simple extensions of ABT for optimization have relied on converting an optimization problem into a sequence of satisfaction problems in order to allow the use of a DCSP algorithm.

Appendix C

Co evolutionary Sociohydrology and Crop Rotation

C.1 Co evolutionary socio-hydrology

It is widely recognized in the field of hydrology that human actions have myriad impacts on hydrological dynamics at the catchment system scale, including via land use changes, the alteration of flow regimes through the construction of dams and weirs, the deterioration of water quality through the pollution of waterways, as well as numerous impacts on biogeochemical cycles and riverine and lake ecology (Carpenter et al., 2011; Montanari et al., 2013). Similarly, it is acknowledged in the social sciences that the well-being of human societies is extraordinarily dependent upon what has been termed the “planet’s life-support system”, not only in terms of global water needs, but also with respect to its role in food production, poverty alleviation, energy production, human health, transport, climate regulation and ecosystem services (Falkenmark, 2001, 2003). Falkenmark (2003, p. 2038) makes the point by saying : “to support the growing world population, balancing will be needed between emerging societal needs and long-term protection of the life-support system upon which social and economic development ultimately depends”. This sentiment is echoed in numerous other studies (Biswas, 1997; Folke, 1998; Rockström et al., 2007, 2009; Varis, 2008). To date, major advances in the disciplines of hydrological sciences and water resources management have helped us understand these challenges, yet it remains critical that we better characterise and quantify the

dynamic nature of human–hydrology interactions, in order that we can effectively manage them in a sustainable manner (Montanari et al., 2013; Thompson et al., 2013)[33]. Notwithstanding that the human activities and natural responses were observed and documented in the past, yet the paradigm of IPWRM has been a framework(as it is in our case study)within which the interaction of the human development and the water resources is explored. However, this approach presumes a broader approach and its output results with a more general picture for the system observed. Here arises the first limitation, where the examination of a single system components in isolation, such as water managements controls to be treated as upper boundary condition to hydrological models(e.g HBV), is insufficient to capture more co evolutionary interactive dynamic between the social demands and nature ,especially for long periods. Therefore it has been acknowledged that the ”soci-hydrology” can bridge the gap that IWPRM can not engage for the isolated subsystems of its framework. Socio- hydrology effectively tackles the holistic integration of the socioeconomic and environmental facets of hydrology, focusing on the exploration of fundamental scientific principles of interactions, feedback and co-evolution of human behaviour with the hydrological system(Elshafei2014)[33].

The main problem is developing a framework coupled model that will integrate the aforementioned aspects. In the following text we are briefly presenting a conceptual framework,that is an extreme simplification of the complex coupled system. Moreover it is a question how to define the drivers of the human and nature feedbacks as well as the responses. And if it is defined then responses? Marginal changes in the social, economic and environmental components of the socio-hydrological system may be driven by exogenous factors external to the catchment (e.g. climate, market prices and demand, political changes) or endogenous factors generated by internal feedback within the catchment (as stipulated in the assumptions and component equations of the model framework). Such changes invariably feed back to the hydrological sub-system via a behavioral response from the human sub-system, since humans will change the rate at which they interact with the catchment water balance(Elshafei2014). Nevertheless another difficulty comes with identifying the state variables and the connections among the three main modeling components.

In figureC.1 there is systematic scheme that is employing all the aspects mentioned before. In relation it is a representation of a complex system dynamics and as it is known the drawback are highly nonlinear tendencies with attractors to certain stable states or

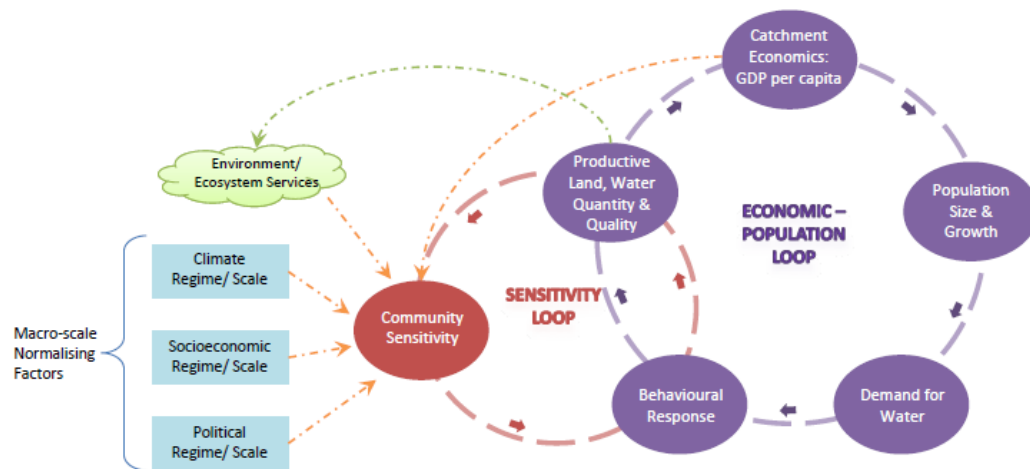


FIGURE C.1: Socio hydrology simplified framework

repellers from unstable states, and thresholds and rapid responses between state transitions may therefore emerge (Scheffer, 2009; Lade et al., 2013). As it can be seen this scheme employs two key feedback loops:

The economic- population loop, expressing the connection between water and the population growth, as well as the GDP dynamics influence. And the so called sensitivity loop modeled on a three-pronged exposure- sensitivity- response paradigm, and introduces a Community Sensitivity state variable. In reference, this one examines the complex coupled human- environment systems.

Anyway the complexity of this new science goes further and different attempts and approaches are met in the recent literature, as a try to model the coupled system. In our case study we tackle the issue of the socio-hydrology in the very beginning introducing the coupled LakeDistrict model and the feedback of the farmers, as well as the planning mitigation measure, the crop rotation. The former is explained in Ch.3. The later as well as other practices related with the farmers behavior and possible improvement of the agricultural system are given in the extent of this appendix.

C.2 Crop rotation and other factors that influence the agriculture

As we mention in the main structure of the thesis, the crop rotation would be eventually the only planning decision that will be taken as recursively periodical action. Different

crops or plants depends of different environmental factors and climate variables in their own specific way. For example, plant development is proportionally influenced by heat units or energy. Daily heat units are determined by finding the mean air temperatures (maximum minus minimum) and subtracting the base temperature (4°C) at which wheat plants cease to grow[34].

Furthermore, the environment to which wheat plants are subjected not only affects development but also determines growth rate. We know that amount and distribution of precipitation, soil type or texture, soil fertility level and soil temperature influence plant growth. Different crops have different nutrient requirements and affect soil balance differently. Some, like corn and tomatoes, are heavy feeders that quickly deplete soil nitrogen and phosphorus. By changing the location of corn each year, you'll be able to renew the plot where it grew the preceding year, so your soil won't get out of balance. There are other crops that also use up nitrogen rapidly. They tend to be the leafy and fruiting crops, such as lettuce, cabbage, and tomatoes. In contrast, root vegetables and herbs are light feeders. Peas, beans, and other legumes add nitrogen to the soil but need lots of phosphorus. Lengthy rotations are sometimes necessary to control chronic soil borne problems. Bean anthracnose fungus can persist in soil for up to three years, so a four-year rotation is needed to keep the disease at bay. The same holds true for such fungal diseases as Fusarium wilt and Verticillium wilt. A few problems, such as club root, persist in the soil for even longer, so rotation is less useful for controlling them. Therefore the crop rotation defined as practice of growing a series of dissimilar/different types of crops in the same area in sequential seasons (Bullock, D.G. 1992. Crop Rotation. Critical Reviews in Plant Sciences) is the one of most recognized necessary techniques that offers to the farmers, abundant harvest, and higher revenue[35]. Well-planned crop rotations has been long recognized as a system that can reduce soil erosion, improve soil structure, enhance permeability, increase the soil microbial activity, soil water storage capacity and soil organic matter content, even though they require diverse agricultural equipment and agricultural supplies which not all farmers can afford. In addition, crop rotation can significantly influence:

- Balance of soil fertility
- Prevent the disseizes and pest attacking the plants
- Give a consistently higher yield

- Optimize the water use
- Reducing the build-up of pests
- Spreading the workload on time
- Mitigating risk of weather changes
- Limiting dependence on agricultural chemicals

Crop's productivity varies according to other agronomic factors. Among them, as different studies show, water demand and stage-dependent sensitivity to water stress play a crucial role: in economic terms, their effect can be evaluated by studying the variation of an indicator frequently called water use efficiency in different irrigation conditions (amount, frequency and operation distribution in time). The water use efficiency represents the crop yield per unit of irrigation water applied and clearly relates the expected harvest amount (and thus the expected revenues) with costs associated to irrigation and water consumption.

In general, the lower the farmer water availability is, the higher is the risk of capital loss (Lavee, 2010), and thus crop choices must be made according to each farmer's water availability. Water demand and stage dependent sensitivity to water stress are relevant pieces of information in the decision-making problem, but their role and ability to influence harvest and costs can be better highlighted by showing their relationships with irrigation technologies features and management options. More information is given in the uncertainty of water supply given in chapter 3, and also in the section C.3.1 where short review is given for the relation among the precipitation, temperature and water supply regarding the irrigation techniques and crop rotation.

Crop rotation, climate variables and water use Irrigation practices and crop rotations should be managed in response to water supplies, considering their impact to the profitability. The choice of crop rotation has important implications for both irrigation and drainage management. The drainage criteria also depend on the crop rotation, the irrigation supply, the irrigation water quality and the leaching fraction (Croon, 1996). Lower yearly drain flow and lower flow-weighted N concentration in drain flow under maize–soybean and soybean–maize than under continuous maize (Ma, 2007). The impacts of crop rotations on the quality of groundwater and rivers and on

the impacts on water resources (shortage, reduced needs for irrigation water). A general remark is that rotations impact water indirectly. Decisive factors are the selection of crops, their use (for grains or green mass), but mainly the level of intensity of production and crop management in general. Five main impacts are addressed in this section (Environmental impacts of crop rotations in the EU,2010)[35]:

- N leaching
- Residues of pesticides
- Erosion
- Evaporation (Evapotranspiration)
- Irrigation

Nevertheless crop rotation and the irrigation techniques are tightly interconnected. In that manner the sequence of chosen crops and the irrigation, influence the crop rotation itself:

- The composition of crop rotation (and consequently of farm cropping plan)
- Crops differ by their water requirements for achieving maximal production. They also differ by their irrigation needs because the ability of crops to extract water from soil and the availability of soil water during the growing season are different from one crop to another.
- The crop sequence
- Some effects of preceding (or previous) crops on water availability for the next crop have been reported in the literature but it is not clear whether they change significantly the irrigation requirements of the next crop.(EC, Environmental impacts of crop rotations in the EU,2010)

In addition different crops refer to different water requirements like:

- High needs of irrigation for water efficient crops, like potato, vegetables, grain maize, which are very sensible to water shortage.

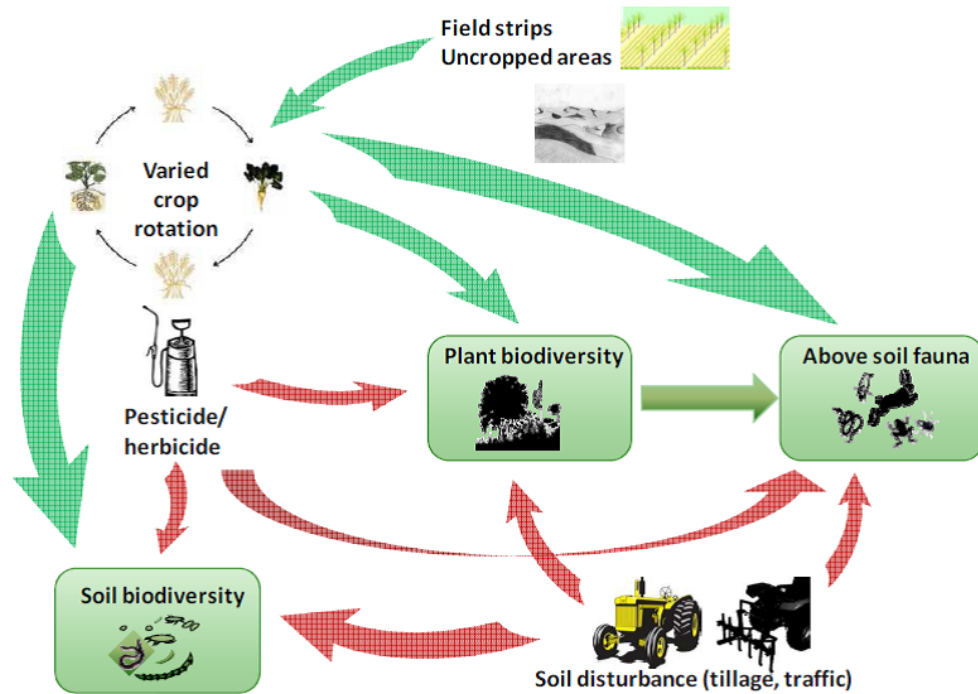


FIGURE C.2: Crop rotation, biodiversity, irrigation techniques

- Drought tolerant crops, like sorghum or sunflower, have efficient adaptive process and can adjust transpiration to water availability, and need reduced amounts of water when irrigated.
- Escaping crops, like winter cereals, escape the summer drought periods in Europe, and are generally not irrigated.

Having the classification of the crops according their requirements, the sequence of crops might be successfully synchronized with the water availability.

Finally it should be added that an agriculture is in fact contributor to the climate change. However the crop rotation itself does have nothing to do with that, on opposite crop rotations may be an effective measure in adaptation and mitigation to climate change. Agriculture contributes to emissions of CO₂ through its use of fossil fuels during cultivations (machinery), and indirectly through energy-intensive inputs, such as fertilizers (especially N), and farming practices, from a general perspective, such as conversion of grassland or peat lands into arable land, tillage practices, etc (Hopkins and Del Prado, 2007). As CH₄ and N₂O have a much greater radiative-forcing potential than CO₂, there is now increasing pressure to curb their emissions in agriculture (Figure C.3).

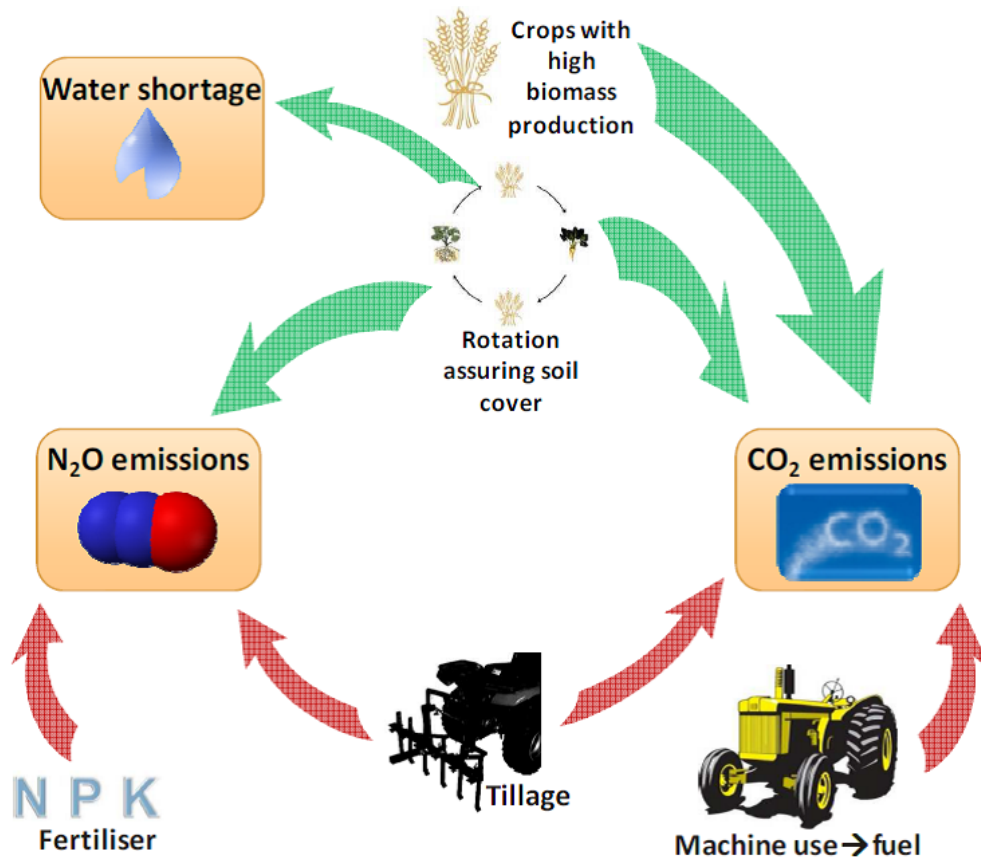


FIGURE C.3: Fertilizers and crop rotation

The practice of rotations in regions threatened by water shortage can contribute to water savings, depending principally on the water needs of crops in the rotation and the soil coverage in order to prevent extensive evaporation.

C.3 OTHER Factors that might influence the Future Planning Problem

Irrigation techniques and technology The most prevalent irrigation technique in Muzza, for the moment being, is the flooding irrigation techniques. In fact the canals of Muzza are one of the oldest in the world and that includes the irrigation as well. And the water demand is directly related with this system requires and the farmers need. However the shift into other more efficient technologies is more than welcome for this system. Of course, the choice to upgrade irrigation structures and equipment to systems with higher delivery efficiency increases the available amount of water allowing, for instance, to plant more water demanding and profitable crops. At the same time this

shift would require investments that farmers, who typically prove to be strongly risk adverse, are not so often willing to do. Well, river, surface (furrow, borderstrip or basin) irrigation, localized (drip, spray, micro-sprinkler, surge, center pivot) and sub-irrigation may be chosen by farmers according to efficiency and costs: for example, large additional investments and operational costs are involved in upgrading to sprinkler, drip or hose pipe irrigation systems, but the returns include significant water savings and in some cases increased crop production. The term irrigation technology is more related with new trends of saving the water, and in that manner strongly connected with the water supply management. There are many new trends and researches about efficient usage of the irrigation water in order to increase the yield and the revenue of the culture as much as possible. But this is out of the range of this study.

Fertilizers and pesticides application Fertilizers and pesticides are commonly used in intensive agricultural systems as the Italian one.

Fertilizer (or fertilizer) is any material of natural or synthetic origin (other than liming materials) that is applied to soils or to plant tissues (usually leaves) to supply one or more plant nutrients essential to the growth of plants. Conservative estimates report 30 to 50% of crop yields are attributed to natural or synthetic commercial fertilizer (Stewart, W.M.; Dobb, D.W.; Johnston, A.E.; Smyth, T.J. (2005). "The Contribution of Commercial Fertilizer Nutrients to Food Production". *Agronomy Journal* 97: 1–) Pesticides are substances meant for attracting, seducing, destroying, or mitigating any pest.(US EPA) They are a class of biocide. The most common use of pesticides is as plant protection products (also known as crop protection products), which in general protect plants from damaging influences such as weeds, plant diseases or insects.

Current fertilizer and pesticide practices are partly based on models and partly on empirical functions obtained in field experiments. These models and functions are updated regularly with new experimental evidence (Bindi and Howden, 2004). Only when the degradation of field conditions appears relevant and agrochemicals application cannot restore the soil balance anymore, fallowing or other crops in rotation are considered.

In reference with these additives that are one of the key points for facilitating the agricultural production, we should highlight that any unplanned action related to them can lead to hazardous environmental reaction. This issue is related with the agricultural pollution. Mostly this pollution is due to the leaching and runoff of the fertilizers and

pesticides, commonly followed by oxidation of the food, eutrophication of the closest water reservoirs or rivers. In that sense farmers should raise their maximum attention using these facilitators.

Best practices Best Management Practices (BMPs) is the term for either structural or operational strategies that land managers (including producers) undertake to reduce the potential for pollution to emit from activities underway on the landscape to both air and water resources. BMPs are designed to benefit water quality and water conservation while maintaining or even enhancing agricultural production. Implementing BMPs benefits both the farmer and the environment, and demonstrates Agriculture's commitment to water resource protection. There are a number of best management practices (BMPs) which agricultural producers can incorporate into their farming practices to decrease their impact on environment.

The general meaning of the BMPs is to perform sustainable agriculture that assumes integrated and participatory management in every branch of the agricultural system. For example soil management, livestock management, integrated pest management (IPM), Nutrient management, and so on, providing one holistic integrated agricultural system. The key principals of BMPs are:

- Integrate natural processes such as nutrient cycling, nitrogen fixation, soil regeneration and natural enemies of pests into food production processes;
- Make productive use of the knowledge and skills of the farmers, so improving their self-reliance and substituting human capital for costly issues.
- Make productive use of people's capacities to cooperate to solve common agricultural and natural resource problems, such as for pest, watershed, irrigation, forest and credit management[36].

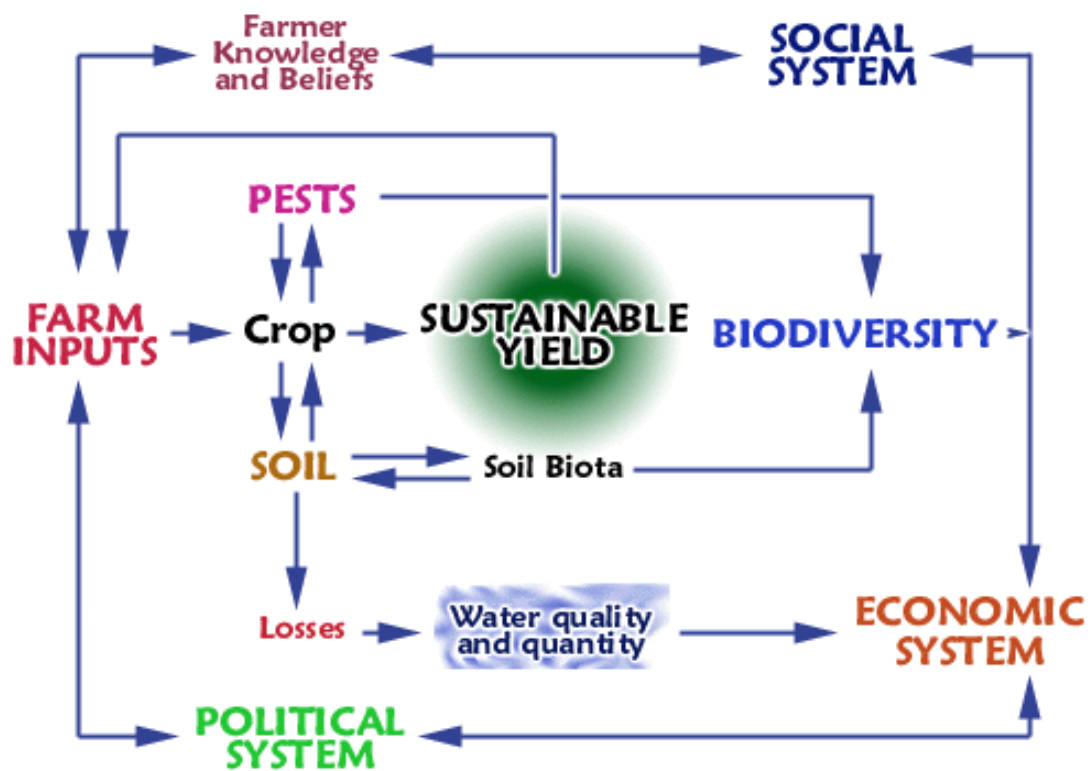


FIGURE C.4: The causal network represents an ideal case of implementing and operating the BMPs.

C.3.1 CC adaptation and cropping system

The entire study above shows that climate change influences agricultural cultivation and directly affects farmers' profit. This implies the necessity of adaptation. In paragraph we anticipated one of the possible adaptation measures.

After all one can ask, what is the purpose of the adaptation? - The purpose of undertaking agricultural adaptation is to effectively manage potential climate risks over the coming decades as climate changes. Adaptation research undertaken now can help inform decisions by farmers, agrobusiness, and policy makers with implications over a range of time frames from short-term tactical to long-term strategic [37]. For example farmers can accomplish short-term climate adaptation, via forecasts, climate modeling and so on. Nevertheless they might find themselves quite limited when long-term strategies are required. The main reason is the diverse uncertainty that is inseparable from the climate models (in details explained in Ch.??).

Some studies even showed that the adaptation can even be profitable for the farmers

comparing with the baseline period, speaking in the light of implementing future projected data (check [38?]). Thus we provide another reason for a future adoption of the climate change adaptive strategies. In that fashion the participation of the farmers in their implementation and research models implementation should be increased. The interaction with the farmers, as direct stakeholders is very important for the final decision and successful implementation. A significant benefit from adaptation research may be to understand how short-term response strategies may link to long-term options to ensure that, at a minimum, management and/or policy decisions implemented over the next one to three decades do not undermine the ability to cope with potentially larger impacts later in the century. In the sections below, we try to identify other key benefits from an increased focus on climate change adaptation. Crop selection is considered critical (Jury and Vaux, 2007), and this agrees with the observations of García-Vila et al. (2008)[38] on farmer's adaptability to water scarcity which is primarily based on cropping pattern changes and on adjustments of irrigation scheduling. In water scarce situations, farmers face the following questions: what crops should they grow? and, how to use best a limited amount of irrigation water?.

Therefore we present the so called **cropping system** adaptations. These adaptations are based on the smart alteration of the management decisions, jointly with the selection of the crops according the yield response to the water diverted for the district of interest. In order to reach higher revenue integrating the crop rotation and the water management the following should be included:

- Altering inputs such as varieties/species to those with more appropriate thermal time and vernalization requirements and/or with increased resistance to heat shock and drought, altering fertilizer rates to maintain grain or fruit quality consistent with the prevailing climate, altering amounts and timing of irrigation and other water management.
- Wider use of technologies to "harvest" water, conserve soil moisture (e.g., crop residue retention), and use and transport water more effectively where rainfall decreases.
- Managing water to prevent water logging, erosion, and nutrient leaching where rainfall increases.
- Altering the timing or location of cropping activities.

- Diversifying income through altering integration with other farming activities such as livestock raising.
- Improving the effectiveness of pest, disease, and weed management practices through wider use of integrated pest and pathogen management, development, and use of varieties and species resistant to pests and diseases and maintaining or improving quarantine capabilities and monitoring programs.
- Using climate forecasting to reduce production risk.

If widely adopted, these adaptations singly or in combination have substantial potential to offset negative climate change impacts and to take advantage of positive ones.

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