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Master of Science in
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Coupling pre-season farmers planning and optimal water supply management to mitigate climate change impacts

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Accoppiamento della pianificazione agricola pre-stagionale e della gestione delle risorse idriche per mitigare gli impatti del cambiamento climatico

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Abstract

Over the last century world population has tripled, and the consequent growing food demand forced agricultural activities to exploit environmental resources more and more intensively. Water availability has nowadays become a limiting factor for agricultural production, and is therefore expected to decrease over the next century due to climate change impacts (IPCC, 2007). Being farming practices strongly sensitive to climatic conditions, adaptation strategies (changing crop types and rotations, shifting sowing and harvesting dates, upgrading irrigation techniques) will be thus essential (Bindi and Howden, 2004). However, changes in water supply management strategies as a response to climate change might impact on farmers' decisions as well.

Up to now, most of research studies has considered the two problems separately despite their clear interdependence, either analyzing the impact of climate change on farmers' decisions for a given water supply scenario or optimizing water supply for different water demand scenarios.

The aim of this thesis is the development of a new methodology, based on an information exchange between farmers and water managers, to integrate the two problems and study the co-evolution and co-adaptation of farmers and water supply systems under climate changes. A model of farmers' decision-making problem was developed to predict farmers' choices on the basis of the expected water availability, and estimate their actual water demand. The operation of the water supply system can thus be re-optimized according to this forecast. Then, farmers can readapt their decisions on the basis of the new optimal operating policy and the loop will be iterated until water demand and supply converge to a new optimal solution.

The interaction between farmers and water managers is expected to enhance the efficiency of water management practices, foster crop production and mitigate climate change impacts, which are assessed through projected hydro-climatic scenarios. The efficacy of the proposed approach was tested on a real-world case study, the Muzza-Bassa Lodigiana irrigation district, located in the North of Italy and belonging to Lake Como water system.

Riassunto

Nell'ultimo secolo la popolazione mondiale è triplicata, e la conseguente crescita della domanda di beni primari ha spinto il settore dell'agricoltura a sfruttare le risorse naturali in maniera sempre più intensiva. La disponibilità d'acqua rappresenta oggi un fattore limitante per la produzione agricola, e si prevede che tenderà a diminuire nei prossimi decenni a causa del cambiamento climatico (IPCC, 2007). Considerata la forte dipendenza delle attività agricole dalle condizioni meteo-climatiche, l'implementazione di strategie di adattamento da parte degli agricoltori (cambiamento di colture e rotazioni, variazione delle date di semina e raccolto, sostituzione di tecniche irrigue poco efficienti) sarà dunque fondamentale (Bindi e Howden, 2004). In aggiunta, possibili azioni di adattamento da parte dei gestori di bacini artificiali potrebbero comportare una riallocazione della risorsa idrica e influenzare ulteriormente le attività agricole.

La maggior parte degli studi condotti finora ha considerato i due problemi separatamente, o analizzando l'impatto dei cambiamenti climatici sulle scelte degli agricoltori dato uno scenario fissato della disponibilità di acqua o ottimizzando la gestione delle risorse idriche per diversi scenari di domanda irrigua.

L'obiettivo di questa tesi consiste nello sviluppo di una nuova metodologia, basata sull'interazione tra agricoltori e gestori, al fine di integrare i due problemi e studiare la co-evoluzione e il co-adattamento delle attività agricole e della gestione delle risorse idriche ai cambiamenti climatici. E' stato quindi sviluppato un modello del processo decisionale degli agricoltori per prevedere le scelte di produzione data la disponibilità di acqua attesa e stimare quindi la domanda irrigua. Questa previsione consente una ri-ottimizzazione delle politiche di gestione di bacini artificiali, in base alle quali gli agricoltori potranno nuovamente adattare le scelte di produzione: il ciclo verrà iterato finché la domanda irrigua e la disponibilità d'acqua non convergeranno a una nuova soluzione ottimale.

L'interazione tra agricoltori e gestori dovrebbe garantire una maggiore efficienza delle politiche di gestione della riserva idrica, aumentare la produzione agricola e mitigare gli impatti dei cambiamenti climatici, che verranno analizzati tramite scenari idro-climatici proiettati nei prossimi decenni. L'efficacia della metodologia proposta è stata testata su un caso di studio reale, il distretto irriguo Muzza-Bassa Lodigiana (Italia Settentrionale) servito dal Lago di Como.

Introduction

Agriculture has always played the fundamental role to provide primary and essential goods to the mankind. But while in the early 19th century its development grew at an exponential rate to meet the needs of the strongly growing world population, nowadays agricultural activities, as many other sectors, have to face the big issue of the limitation of environmental resources (Rosegrant *et al.*, 2002). On one hand, in many countries, for instance Italy, almost the whole national territory that could be dedicated to agriculture was actually converted to cropland. On the other hand, in recent years the interest towards renewable energy sources led to a partial shift of the target of agricultural production activities from food to energy production purposes. The combination of these two trends, namely saturation of the available territory and partial shift to energy production objectives, led to a main consequence: in order to satisfy increasing energy and food demands, agricultural systems had to increase the cropping intensity, by means of higher water consumption and fertilizers, pesticides and other chemicals application. As a result, the resulting pressure on the environment increased dramatically (Bonell and Askew, 2000).

In order to deal with the limitation of water resources and settle the consequent conflicts arising among different water users, the Integrated Water Resources Management (IWRM) paradigm is being adopted more and more frequently. This holistic approach aims at facing decision-making processes in an integrated and participatory way, accounting for the opinion of all the parties (stakeholders) involved, in order to build a strong consensus around the decisions to be taken (Soncini-Sessa *et al.*, 2007). A consequent fundamental innovation brought by the IWRM approach is thus a strengthening of communication and information exchange between stakeholders and Decision Makers.

This work is focused on the agricultural sector, and proposes an innovative methodology to face the issue of the limitation of water resources by exploiting the enhanced interaction between stakeholders and Decision Makers guaranteed by the IWRM approach. Specifically, if farmers' choices could be predicted in advance (e.g. at the beginning of the year), water supply systems (e.g. the regulation of an artificial reservoir for irrigation purposes) could be tuned to match the estimated water demands of downstream irrigation districts and thus strongly reduce water wastage. Nowadays, in fact, a strong inefficiency characterizes water management practices and is mainly due to the fact that Regulators plan the releases from the reservoirs on the basis of a fixed water allowance, which is assigned to downstream users by regulations and district-level agreements. Thus, the evolution in time of agricultural activities cannot be accounted for in reservoirs operating policy design, and consequently water might be available to farmers in moments when it is not needed and viceversa. In order to increase the efficiency of water releases and foster crop productivity at the same time, the actual downstream water demand should replace the regulated water allowances in the operating policy design phase. This solution could strongly increase the water use efficiency and enhance the sustainability of the current water systems management.

Furthermore, this strategy would also allow to mitigate climate change impacts. Climate change will very likely cause a strong modification of water regimes all over the world and much more frequent droughts and water shortages than nowadays (at least in temperate regions). In addition, according to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007), the impacts of high temperature and heavy precipitation events will probably combine to depress crop yields and to increase yield fluctuation risks in many regions. Thus, if no adaptation strategies aiming at a redistribution of water availability in space and time and a modification of current farming practices are developed, negative impacts on agricultural activities as a result of climate change could be substantial. In the long run, the growing demand for primary goods could not be met by the agricultural supply anymore.

The basic goal of this work is to assess the effectiveness of the proposed information exchange between water demand and water supply. Moreover, assuming that water availability might decrease over the next century as forecasted by IPCC (2008), current water management strategies will tend to become even more inefficient. The second aim of this thesis is therefore to estimate the potentiality of the proposed approach to mitigate climate change impacts on agricultural production activities, comparing this solution with the business-as-usual case, namely if no adaptation strategies are implemented.

In order to achieve these goals, the following procedure was followed. The first step is the development of a model describing farmers' decision-making process aimed at predicting their choices for the coming year: specifically, the model determines the optimal crop allocation that maximizes farmers' income and thus estimates their actual water demand. The operating policies of upstream reservoirs can be thus re-optimized with more realistic inputs representing farmers' actual water demands. The decision chain is the following: operating policies are optimized in the first place and then farmers adapt to the expected water releases in the coming growing season. However, while nowadays this decision chain is unidirectional (operating policies are independent of farmers' decisions, being designed on the basis of regulated and stationary water allowances), the information loop connecting operating policies design and farmers' decision-making process creates an interdependency (a feedback loop) which requires to solve the problem through iterations that will stop once convergence between water supply and demand is reached.
The coupled model described above was applied to the study area of the Muzza irrigation district, located in the Padana Plain in the North of Italy, in order to assess the potential beneficial effects of this new methodology in a real world situation. In particular, the effectiveness of the proposed approach was tested in two different climatic scenarios, namely current and forecasted meteorologic conditions, and in this latter case the beneficial effects of farmers' and Regulator's co-adaptation to climate change assessed.
The thesis is organized as follows:

- Chapter 1 introduces the potential impacts of climate change on water availability in the next century and possible adaptation measures, describes an innovative decision-making paradigm based on the interaction and information exchange between stakeholders and Decision Makers and finally details the main goals and purposes of this work;

- Chapter 2 provides an exhaustive description of farmers business and decision-making process from a qualitative viewpoint, highlighting typical decisions that farmers generally take to plan crop production activities and the factors and determinants affecting their adoption;

- Chapter 3 formalizes farmers' decision-making process and water supply management optimization in mathematical terms, describes the criteria followed to build the information loop to integrate the two problems and clarifies how climate change impacts assessment is undertaken;

- Chapter 4 introduces the case study and describes the numerical results obtained in both current and climate change conditions;
- Chapter 5 draws the main conclusions, summarizes the most relevant results achieved and suggests possible directions for future research.

Chapter 1

Context and framework

1.1 Climate change impacts on water availability

Water will shape the new century, just as petroleum shaped the one that has just passed. Over the last century the population of the planet has tripled, while water consumption has increased by six or seven times. Consumption of water has increased at double the rate of the population, and as a consequence 30% of humanity does not have sufficient water and each year 7 million people die from diseases caused by polluted water. The forecasts are that in 2025 the world population will be about 8 billion and that the fraction with water scarcity will rise to 50% (Rosegrant *et al.*, 2002).

In developing countries, where agriculture is an important component of the economy, irrigation uses from 75 to 90% of the fresh water derived from rivers or pumped from aquifers, but also in developed countries, where agriculture employs less than 5% of the inhabitants, agricultural water consumption is still very high, between 50 and 65% of the total, as shown in Figure 1.1. This means that the competition for water between agriculture and the other sectors is very high and destined to increase with population growth (Bonell and Askew, 2000).

In addition to a strongly increasing trend of world population and consequent water demand, climate change is expected to affect the hydrological balances and regimes: water availability is forecasted to change all over the world, as recently assessed by the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007). Changes in the distribution of river flows and groundwater recharge over space and time will be determined by changes in temperature, evaporation and, particularly, precipitation (Chiew, 2007). Some climate change impacts on

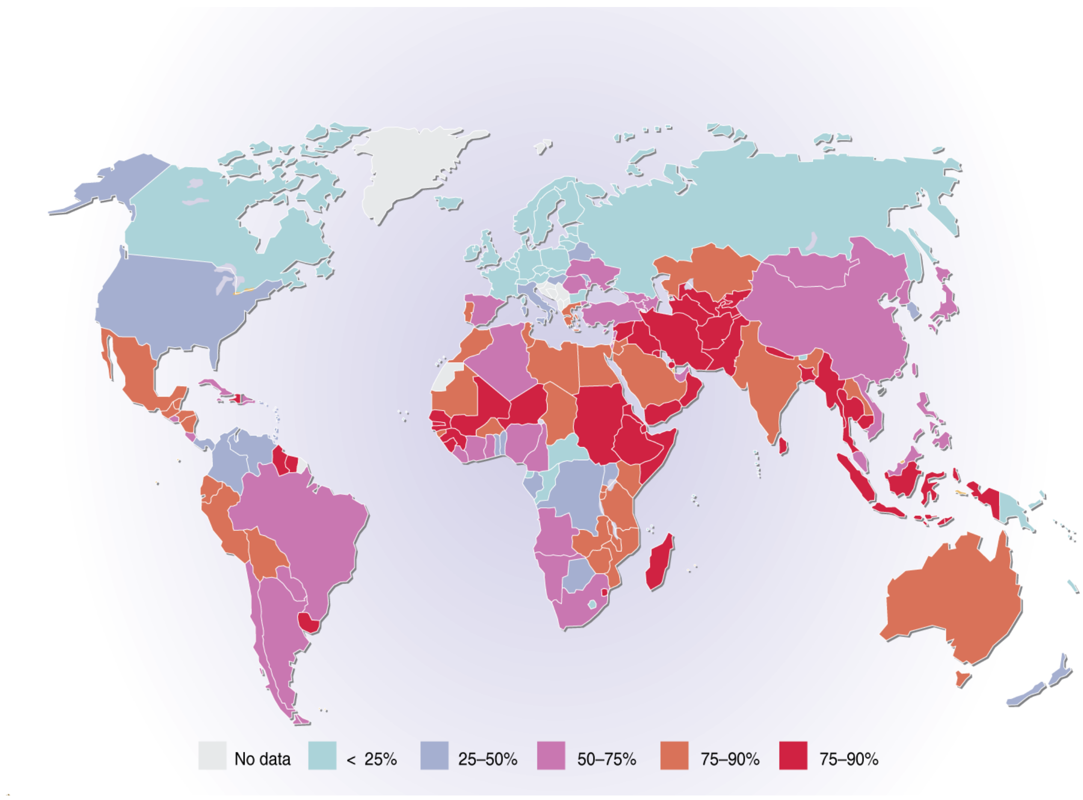

Figure 1.1: Proportion of water withdrawal for agriculture in year 2001 (FAO, Aquastat, 2007).

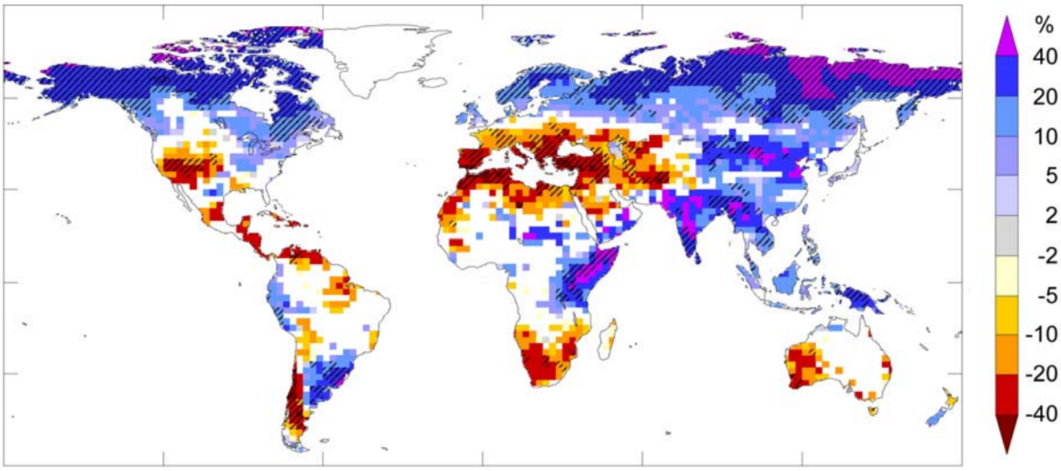

Figure 1.2: Large scale relative changes in annual runoff for the period 2090-2099, relative to 1980-1999. White areas are where less than 66%of the ensemble of 12 models agree on the sign of change and hatched areas are where more than 90% of models agree on the sign of change (IPCC, 2008).

hydrological processes have been observed already (IPCC, 2007), and further changes are expected.

Runoff is projected to increase in some regions and to decrease in others, causing problems of water excesses in some catchments and water shortages in others (see Figure 1.2). Areas in which runoff is projected to decline are likely to face a reduction in the value of the services provided by water resources, e.g. as habitat for freshwater fauna and flora, or as energy source. In addition, a shift in winter precipitation from snow to rain, as temperatures rise, leads to a change in the timing of the peaks of stream flow in many continental and mountain regions. The spring snow melt peak is brought forward or eliminated entirely, and winter flows increase. Therefore, as glaciers retreat due to warming, river flows will increase in the short term but decline once the glaciers disappear (Kundzewicz *et al.*, 2008).

Moreover, changes in flood and drought frequency and intensity are also projected. The proportion of total rainfall from heavy precipitation events is very likely to increase over most areas (IPCC, 2007). The flood frequency and magnitude is projected to increase in the regions experiencing increase in precipitation intensity, while drought frequency is projected to increase in many regions, in particular those where reduction of precipitation is forecasted, as Figure 1.3 shows. Globally by the 2090s,

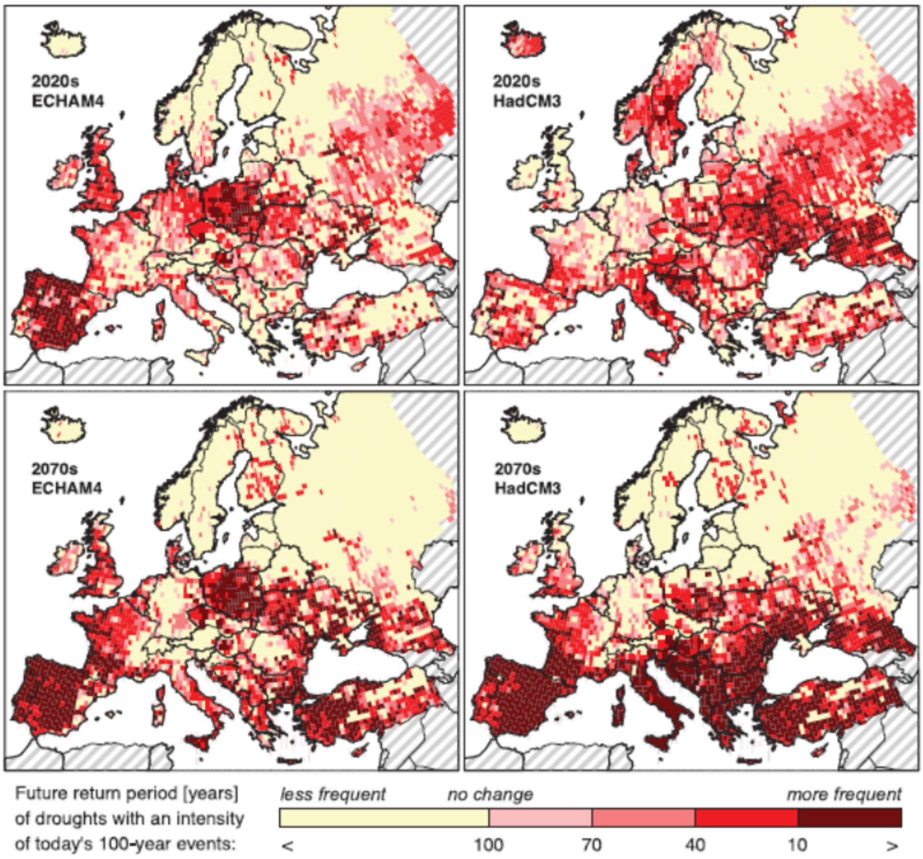

Figure 1.3: Change in the future recurrence of 100-year droughts, based on comparisons between climate and water use in 1961-90. The acronyms ECHAM4 and HadCM3 indicate two General Circulation Models used to forecast climatic conditions in the future at a global scale (IPCC, 2001, 2008).

drought-affected areas are likely to increase in extent, while the proportion of the land surface in extreme drought at any one time is predicted to increase ten-fold from the present (*ibidem*). However, the beneficial impacts of projected increases in annual runoff in such areas as eastern and southeastern Asia, will be tempered by adverse impacts of increased variability and seasonal runoff shifts on water supply and flood risk, in particular in heavily populated low-lying river deltas (Kundzewicz *et al.*, 2008).
Taken together, these potential changes in the volume, timing and quality of surface water and groundwater will impact, to varying degrees, on the reliability and availability of water supplies for civil, industrial and agricultural purposes, on the exposure to flood events, on water-borne transport and tourism, and, of course, aquatic ecosystems (IPCC, 2001).
The magnitude of the impacts, however, will not only depend on the changes in water resources, but also on the effectiveness of adaptation strategies that water managers and users will be able to undertake (Arnell, 1998).

1.2 Integrated Water Resources Management

In order to deal with the growing water scarcity and manage water resources more efficiently to effectively face projected climate change impacts, Decision Makers[1] should decide water allocation in space and time by developing a coordinated strategy aimed at involving all the stakeholders in the decision-making process, in order to define actions with wide consensus and hence better chances to be successful. In water resources management problems, the most common stakeholders are downstream water users: cities or villages need water for industrial and domestic purposes, agriculture uses it for irrigation, hydroelectic powerplants exploit its flow for electricity production, but many other stakeholders may exist.
However, besides the plurality of the *U*sers, two other *U*s must be considered (as an effective slogan created by UNESCO suggests): the *U*ncertainty, that is intrinsic

[1] In general terms, the Decision Maker is the person or authority that is in charge of selecting the best compromise alternative among all the possible ones according to all the stakeholders' interests. In this work, the terms "Decision Maker", "water resources manager" and "Regulator" will be used as synonyms. The stakeholdes are those people, institutions, companies, organizations or agencies that will experience some direct or indirect effects of the decisions to be taken.

to the dynamics of water resources and is constantly strengthening while climate change advances, and the complexity of its *U*ses. In other words, it is necessary to account for the interdependence and co-evolutionary development of physical aspects of the problem at hand (hydrological, climatological, ecological), as well as the non-physical ones (technical, sociological, economic, administrative, legal), considering them from all the points of view from which all the different stakeholders judge them.
In summary: the point of view must be holistic and decisions integrated and participatory to promote consensus-based decision making. This is the management paradigm that is being sought today and that is synthesized in the acronym IWRM: Integrated Water Resources Management (GWP, 2003). To put this into practice it is necessary to activate a decision-making process that

> *...promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner, without compromising the sustainability of vital-ecosystems. (GWP, 2003)*

This process needs to be bottom-up, and not top-down as in the traditional way to address problems: this allows to construct a holistic and shared framework which embodies all the individual viewpoints as partial, but equally considered, viewpoints (Soncini-Sessa *et al.*, 2007).
Integrated Water Resources Management should also be an instrument to explore adaptation measures to climate change. On the water supply (i.e. Decision Makers') side, successful integrated water management strategies could include reshaping planning processes and coordinating water resources management on the basis of projected climatic changes (IPCC, 2008). However, integrated strategies should also foster a better communication between stakeholders and Decision Makers, allowing more frequent information exchanges and coordinated decisions. Thus, the bottom-up consensus-based decision-making approach, which IWRM is based on, not only allows the Decision Maker to account for the viewpoints of all stakeholders, but also to interact directly with them and understand better their needs and expected demands: in this way, water managers' decisions can be taken not only in an equitable, but also efficient manner.
The enhancement of the interaction between stakeholders and Decision Makers is the key problem that this work aims to study, as will be better explained in the following Sections: a more cooperative behavior could foster the efficiency of current

water management practices and facilitate a joint development and implementation of possible co-adaptation strategies to climate change.

1.3 Water supply and demand adaptation measures

In order to effectively face a changing climate, adaptation strategies need to be undertaken by both water managers and users.
As concerns the water supply, attention has to be devoted to understanding and managing the transition from current planning and management practices to more adaptive ones that take into account the changing climatic conditions as well as environmental, technological, economic, institutional and cultural factors. This implies a paradigm shift in water management from a "prediction and control" to a "management as learning" approach, able to tune management practices on the basis of new experiences, understandings and insights (Pahl-Wostl, 2007). Adaptive water management refers thus to a systematic process for continually improving water management policies and practices by learning from the outcomes of implemented management strategies. Climate change impacts could be counteracted by means of a continuous learning process, which would allow to adapt water allocation in space and time on the basis of continuously updated information about climatic conditions and trends (e.g. those highlighted in Section 1.1).
However, a very similar adaptive behavior and learning approach are advisable on the water demand side as well, since the best climate change mitigation results could be achieved only if co-adaptation of water supply and demand takes place, as the IWRM paradigm suggests.
In this work, the set of water users considered in the Regulator's decision-making process for water resources allocation is restricted to farmers. Global warming has the potential to greatly influence agriculture worldwide because of the sector's obvious dependence on weather and climatic conditions (Paudel and Hatch, 2012). Farmers should be able to mitigate the negative impacts or take advantage of possible positive effects of climate change on crop yields by developing appropriate adaptation strategies (IPCC, 2007; Bindi and Howden, 2004; Howden *et al.*, 2007; Deressa *et al.*, 2009; Rosenzweig and Tubiello, 2007; John *et al.*, 2005; Seo *et al.*,

2005). Adaptation options include changing crop types (e.g. more resistant ones) and rotations, adopting Best Management Practices to retain moisture in the soil and foster its productivity, upgrade irrigation techniques to reduce water losses and shifting sowing and harvesting dates to match crops' temperature requirements. Quantitative results were found by McCarl (2008), who projected the impact of climate change on US crop yield in 2030 and 2090 under adaptation and no adaptation scenarios based on different climate change models and found that crop yields are likely to increase by 3-88% in 2030 and by 5-35% in 2090 under no adaptation scenarios, whereas yield increases are even greater if adaptation takes place.
The efficacy of adaptation strategies undertaken by both water supply and demand has been thus extensively assessed by research studies.

1.4 Thesis goal and structure

As reported by IPCC (2008), the application of IWRM to develop adaptation strategies coordinated between water managers and users to counteract climate change impacts is currently just in its infancy. As the reference list in Section 1.3 shows, great research efforts have been focused on analyzing the two problems – water supply and demand – but they have always been addressed separately: some of them focus on the water supply management and simulate the adaptation of reservoirs operating policies to climate change on the basis of a given estimate of the downstream water demand; some other studies, on the opposite, assume a fixed water supply and test farmers' adaptation under some forecasted climatic conditions. Thus, despite the great effort to study possible adaptation measures in agriculture and water management, no research studies have ever addressed the problem of co-adaptation and co-evolution of agricultural and water supply systems in a changing climate, which is exactly the main focus of this work.
In this thesis, attention is thus focused on the relationship existing between water management (i.e. operating policies) optimization and water demands generated by agricultural production activities: the ultimate goal is the development of a model able to integrate the two problems, which, as said, have been solved separately so far, despite their clear interdependence. The reason why no integration between the two problems has ever been attempted probably consists in the fact that nowadays

water releases from regulated reservoirs are very frequently optimized on the basis of the maximum amount of water that each downstream stakeholder is allowed to withdraw. These *water allowances* were fixed by regulations and district-level agreements which date back to several decades ago, and have not been changed since then, even though agricultural activities have been evolving continuously to adapt to market variations and trends or to reduce risks of capital losses if droughts or extreme climatic conditions are forecasted for the coming year. The intuitive result is a strong inefficiency of the current operating policies because they are designed on the basis of fixed water allowances, whereas farmers' actual water demand is not the same in consecutive years since it varies according to their annual decisions: if the actual water demand arising from their production plan is higher than their water allowance crop production activities will be damaged because water stresses will hinder crops growth; if, on the opposite, their actual water demand is lower than their water allowance, they will tend to withdraw as much as they can anyway and over-irrigate their crops, causing a significant water wastage.
If instead reservoir operating policies could be recursively optimized every year according to the expected farmers demands deriving from their scheduled crop production activities, inefficiencies could be strongly reduced. This result could be achieved by means enhancing the information exchange between farmers and Regulator (as advised by the IWRM approach), who could co-adapt their choices thanks to this interaction. Thus, in this perspective, the first basic goal is to develop a model able to simulate farmers' decision-making process and thus predict their decisions in advance (e.g. for the coming year): specifically, given a forecast of the relevant external factors (e.g. water availability and hydro-meteorological conditions), the model identifies the set of decisions (e.g. kind of crops to plant) which optimizes farmers' objective function (e.g. income maximization) and generates their expected water demand accordingly. This latter output can be used to re-optimize the operating policy from the upstream reservoir and thus tune the amounts and timing of water releases consistently with the water demands of those crops that will be actually planted. As a consequence, flexibility, effectiveness and efficiency of reservoir management could be highly enhanced: operating policies would be able to adapt to possible sudden changes in crop production activities even in consecutive years, reduce crops' water stresses and thus increase final yields and profits, reduce water wastage and ultimately enhance the sustainability of agricultural systems at the same time.

If current operating policies are already not optimal because designed on the basis of fixed water allowances instead of evolving water demands, their inefficiency in meeting the needs of downstream users is very likely to increase over the next century. Climate change will bring about extreme events, among which water shortages (in temperate regions) and higher temperatures. Droughts are therefore likely to become more and more frequent, thus if operating policies do not adapt to these changes, crop production activities could be strongly damaged. Therefore, farmers' water demand is likely to vary strongly in the future due to possible implementation of adaptation strategies and thus a diverging trend between current water allowances and actual irrigation demand can be reasonably expected.
On the basis of this consideration, the second basic goal of this work is to test the efficacy of the interaction and information exchange between farmers and Regulators in mitigating climate change impacts: specifically, two behavioral scenarios – adaptation and no adaptation to climate change – will allow to assess the different forecasted impacts on crop production activities and thus the potential beneficial effects of the implementation of adaptation strategies.

It should be quite intuitive that the final goal which this work envisions is too ambitious to be accomplished within this thesis: modeling farmers decision-making process to forecast their decisions in a reliable and realistic way would mean, in fact, to build a numerical model simulating their whole business. The main goal of this work is thus different and consists in exploring the possibility of an integration between operating policies design and farmers decision-making process through the development of an innovative methodology, understanding the potential beneficial effects deriving from this coupling and laying the foundations for further developments that will be likely to achieve more realistic results, at least concerning the reliability of predictions related to farmers' optimal choices.

Chapter 2

Problem formulation

Farmers' business is composed by many different activities which must be planned and scheduled periodically. As far as crop production is concerned, the management and profitability of farmers' activities are strongly affected by two main external driving forces: the hydro-climatic and the socio-economic conditions. The former includes the forecasts of meteorologic conditions and the expected water availability during the coming year; the latter instead includes variables related to the market of agricultural products, e.g. the expected sale price of each crop and the relative demand.

Hydro-climatic conditions

Hydro-climatic conditions significantly affect farmers' decisions because crops' growth process closely depends on many meteorological variables, among which the average daily temperature, precipitation, humidity, wind speed and net solar radiation. In recent years, the Intergovernmental Panel on Climate Change (IPCC, 2007) has given proof that climate change, which mankind is already perceiving, will lead to much stronger variations of these environmental variables over the next century than those we experienced so far. A few scenarios describing some possible patterns of climatic evolution in the coming decades were also developed (IPCC, 2000) and many research studies focused their effort on the attempt to assess the potential impacts that each of them may have on human activities. Despite the variability of the quantitative results due to the high degree of uncertainty characterizing the problem, the general understanding and acknowledgement is that climate change is expected to strongly modify current climatic regimes and affect water availability and balances all over the world. As far as agricultural practices are concerned, the potential of climate change to strongly modify crops' growth and thus affect farmers' business over the next century has been assessed beyond any reasonable doubt. If no adaptation strategies to counteract climate change impacts (e.g. more frequent droughts and high temperatures) are implemented, agricultural production may face strong yield and revenues reductions over the next decades. Some possible adaptation options include adopting Best Management Practices to save humidity in the soil, shifting sowing and harvesting dates, upgrading irrigation techniques to reduce water losses or even changing crop types and rotations. The crop choice pattern is exactly the main focus of this work.

Socio-economic factors

The implementation of the adaptation options listed above depends on the results of a cost-benefit analysis that farmers – more or less explicitly – carry out to evaluate their economic convenience. Water saving adaptation measures have been extensively proved to increase crop yields and thus the profitability of agricultural activities under many different climatic conditions. The profitability deriving from the modification the crop choice pattern requires instead a more attentive evaluation. Each crop typology is characterized by typical agronomic features which determine the crop growth process: some crops show a strong resistance to water stresses, meaning that higher water stresses are necessary to have the same yield reduction as sensitive crops. Intuitively, the forecasted reduction of water availability for farming activities should lead to the diffusion of adaptation strategies aimed at replacing sensitive with resistant crops. However, since the most sensitive crops are also, in general, the most profitable ones, if yield reductions are compensated by high sale prices farmers could decide not to modify their crop choice pattern. From these considerations, the key role played by the crops' market price on the adoption of adaptation strategies is evident.
The Supply and Demand theory, developed by the classical economics, suggests that the price of a certain good in a highly competitive market is given by the intersection between demand and supply curves: given a fixed demand curve, if the supply increases the price decreases and viceversa. This principle can be applied to the case

of farmers: given a forecasted demand curve of a specific crop[1] and being the market of agricultural products characterized by a high competition, the crop price will be determined by the amount of that crop that is available on the market. Farmers' decisions and adaptation strategies will thus depend on other farmers' choices and could be thus studied through an agent-based approach.
However, the real mechanism of market price formation involves many other factors and disturbances that were not considered in this simplified description. For instance, as a starting point, it would be necessary to assess the influence that farmers' adoption of a certain crop has on the crop's market price: if the market supply is in fact several orders of magnitude higher than each farmers' production (i.e. the market of agricultural products is actually highly competitive as just hypothesized), the decisions taken by a few farmers cannot influence the market price, which could be reasonably assumed as independent of the quantities produced. This is exactly the main price-related assumption of this work: given the limited time and space available, the market price formation problem was disregarded and the profitability of each crop, which determines farmers' choices, was evaluated assuming a fixed crops' prices, as will be better explained in Section 2.1. A similar assumption was also made by Paudel (2012) while modeling farmers' decision-making process.

Water supply management

The future of agricultural activities will not only depend on farmers' ability to adapt to climate change: the response of water supply systems to the variation of the climatic conditions will play a crucial role, too, since it will affect water availability for farming practices. The best response to mitigate climate change impacts on agricultural activities would thus be a full adaptation by both farmers and water supply. On one side, the allocation of water availability in space and time would need to be re-optimized to match crops' actual water demand and minimize water wastage. On the other side, changes in water supply management strategies might impact on farmers' decisions as well, e.g. leading them to select less water demanding crops if water availability decreases as forecasted. Operating policies should be re-designed once more to match the new farmers' choices and thus an *information loop* could be

[1] The demand curve could reasonably be the estimated as equal to the one of the previous year (which different statistical institutes publish on the web) unless some strong trends are taking place, e.g. the interest in energy crops for biofuels and electricity production purposes.

created between farmers and Regulator: the problem could be solved by reiterating the information exchange until convergence is accomplished and hence an equilibrium solution is found.
The interdependence existing between FDMP and Water Supply Management Optimization Problem (WSMOP, from here on) is exactly the key problem that this work aims to tackle. In fact, as mentioned in Section 1.3, in literature there exist several studies which addressed the two problems separately. The methodology developed in this work, instead, aims at addressing the problem from an innovative and integral point of view, by means of the development of a unique numerical model (the *Coupled Model*, from here on) which integrates FDMP and WSMOP and thus allows to study the effects of a co-adaptation of farmers' and Regulator's choices under a changing climate. Figure 2.1 completes the graphical representation of the logical thread followed by this thesis work with the above considerations.
The methodology developed in this work is expected to lead to significant improvements in crop production and, at the same time, a strong reduction of water wastage (water releases happening in moments when they are not required). This work envisions, in fact, the possibility that the same amounts of water could be released during the year with the timing and quantities actually required by the crops planted in downstream irrigation districts: this would allow to minimize crops' water stresses and thus increase crop yields and the deriving revenues, as well as guaranteeing or even enhancing the environmental sustainability of irrigation activities by improving the water use efficiency. In addition, the water demand and supply matching is expected to generate beneficial effects on crop production activities not only under the current climatic conditions, but especially in the long term, since the negative impacts caused by the forecasted contraction of water availability due to climate change could be mitigated.

Integration between FDMP and WSMOP: the details

The expectation of achieving the beneficial effects described above by integrating FDMP and WSMOP is justified by the strong inefficiency that characterizes current water supply management practices. Nowadays, reservoir operating policies are optimized on the basis of the *historical water allowance* of downstream irrigation districts, which is defined by regulations and district-level agreements. But this is

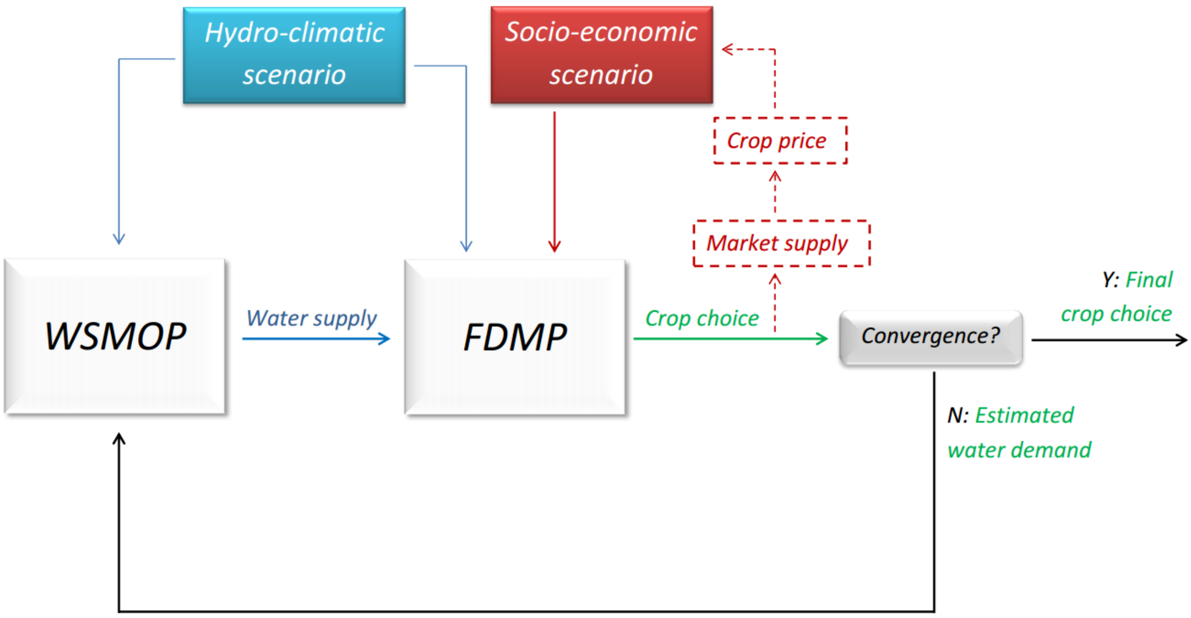

Figure 2.1: Structure of the complete reasoning followed in this thesis work: the mechanism on the basis of the integration between FDMP and WSMOP is shown, as well as the main driving forces acting on the two problems. The dotted line highlights the feedback loop that could be created if future investigations tackle the problem of crops' market price formation.

not necessarily close to the expected one for the following year. Every year, in fact, farmers' decision about the allocation of land to each crop typology varies according to market demands, expected prices and many other factors that will be mentioned in the following Sections: hence, along with it, the water demand changes year by year as well. This simply means that the current way of optimizing water releases from upstream reservoirs makes use of inputs that are not representative of the real situation and, therefore, the resulting strategy is very likely to be sub-optimal.

The Coupled Model is able to tune the water releases from upstream reservoirs according to the expected water demand for the following year derived from the expected land allocation to each different crop. Specifically, the output of FDMP model will be an estimate of downstream irrigation districts' water demand according to the estimated optimal farmers' choices on crop production for the coming year. The water demand estimate is the input to the WSMOP model, which re-optimizes the reservoir operating policy according to the forecasted farmers' demands. The new optimized policy, in turn, will be used again as input to FDMP: farmers will be allowed to adapt their crop production choices according to the new operating policy and thus to the expected water availability for the following year. This adaptation will generate a new estimate of the water demand, that will be used once more in WSMOP to re-optimize the operating policy and so on. This information loop will be reiterated just before the beginning of each year until some convergence criteria will be met[2].

The expected final result is an optimal operating policy of upstream reservoirs, tuned to match – as much as possible – the water demands of downstream irrigation districts during the whole year. It is quite intuitive that a perfect match between water demands and releases will not always be possible: some water deficits still may happen during particularly dry years or, for instance, when farmers, due to some particular market trends, decide to plant more profitable crops even though they require more abundant water volumes than the available ones (in this case the yield reductions due to water stresses could be compensated by higher sale prices).

Being the integration of FDMP and WSMOP accomplished through a loop, it is straightforward to describe and formalize them separately. For this reason, the cur-

[2]See Chapter 3 for the definition and formalization of the algorithms and numerical models that will be used.

rent Chapter is aimed at providing a solid – for the aims and purposes of this dissertation – theoretical background concerning the Farmers' Decision-Making Problem, whereas in Chapter 3 FDMP and the WSMOP will be formalized from a mathematical standpoint and coupled together to assemble the loop described above.
Thus, with the perspective of delving into the irrigation water demand prime causes and determinants to generate more realistic and representative expected water demands as inputs to the WSMOP, the focus of this Chapter will be mainly on the general structure of the model describing FDMP (Section 2.1), the nature and features of the possible choices that farmers can make in their decision-making process (Section 2.2) and the most relevant factors and driving forces affecting them (Section 2.3).

2.1 General description of Farmers' Decision Making Problem

As in every entrepreneurial activity, the main goal of farms is to create profit and maximize revenues and thus every decision will be taken in this direction.
Farmers' business is traditionally centered around two main activities, which are often connected and significantly influence one another from an economical and logistical standpoint: crop production and livestock farming. As a simple instance, their connection and reciprocal support becomes economically relevant in terms of avoided costs when part of the crop production is used as animal feed and livestock manure as fertilizer for cropped fields. Hence, a detailed economic balance of farmers' business should account for all similar connections and correlated *shadow-prices*[3], which, in turn, affect considerably the overall profitability. This thesis focuses on understanding the relationships and mutual influences between profit creation through crop production activities – the basic goal of farmers – and the arising water demands. For this reason, livestock farming and all its hidden influences on the economic balance of crop production will be sometimes mentioned in the theoretical treatise but disregarded in the numerical analyses carried out in this thesis.

[3]The shadow price is the infinitesimal change in the objective function arising from an infinitesimal change in the constraint.

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 and the expected sale prices (Mejias *et al.* (2003)).
In general terms, the periodicity of a decision depends on the nature of the decision itself: planning decisions (e.g. the upgrading of the irrigation technique) are generally taken once and for all, whereas management actions (e.g. the application of fertilizers) are typically taken frequently or periodically (Soncini-Sessa *et al.*, 2007). However, in the case of FDMP, some decisions (e.g. the crops to plant) show intermediate features as they can be reviewed periodically but cannot be altered during each period (the crop growing season). For this reason, FDMP can be formalized as a *recursive planning problem* (see Section 3.2).

The general structure of a FDMP is quite simple. Just before the beginning of the y-th year, farmers plan their production activities by means of a decision-making process that is based on an exhaustive *simulation-based optimization*: by means of a *crop growth model*, farmers obtain the expected crop yield at the end of the year which allows them to select the set of (optimal, feasible and coherent) planning and management actions, among which the land allocation to each crop, that maximize their *objective function*, namely the expected income deriving from end-of-year sales of crop products on the market. During the growing season (from January to December) of year y, farmers will be able to implement only pure management actions.

Farmers' objective function can be easily evaluated as the product between expected marketable biomass grown during the year and the expected sale price. The former can be computed through a crop growth model and 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. As concerns the socio-economic conditions, it is worthy to highlight that the exact sale prices are unknown to farmers when they plan their production activities: in fact, sales will generally start at the end of the year (in the case of single-year crops) whereas farmers' planning is carried out before the beginning of the growing season. For this reason, farmers' planning cannot but rely on crop prices forecasts and trends in the last few years, thus a remarkable price-related degree of uncertainty intervenes in the decision-making process. However, building a model to describe prices dynamics in a reliable way, despite absolutely useful to increase the representativeness of FDMP model if integrated with it, is quite challenging and goes beyond the scopes and purposes of this work and will be in fact included in the future developments in Chapter 5. In this work, crops sale price will be considered as an uncertain disturbance, namely a disturbance acting on the system whose probability density function in unknown but its feasible values (deterministic scenarios) are known. In general, optimization problems should be solved for each of the possible deterministic scenarios and an optimal solution should be determined for each of the possible realizations of the uncertain disturbance: however, as a simplifying assumption aimed at reducing the computational load, only one deterministic scenario will be considered in this work. The expected prices will thus be unique and fixed when farmers optimize their choices at the beginning of the year, thus neither price models nor forecast methods were implemented in this study.

2.2 Possible farmers' choices

The main goal of this Section is to describe the different actions that farmers may decide to implement, namely the feasibility set of farmers' decisions which the simulation-based optimization process evaluates to determine the subset that optimizes farmers' objective function.
Crop production involves a great number of activities and tasks which can be carried out in different ways and lead to different economic impacts, depending, for instance, on farmers' appliances and capital availability, risk aversion and many other internal (farmer-dependent) or external (environment-dependent) factors that will be listed and reviewed in Section 2.3. As already mentioned, farmers' decision-making process consists in taking periodical (annual, in this work) recursive planning actions to maximize the end-of-year expected revenues. In the following Sections, the nature and characteristics of farmers' possible actions and their mutual dependencies are described and detailed.

2.2.1 Crop types

Among all the decisions that farmers are expected to take periodically the typology of crops to plant is clearly paramount: all other decisions are taken in the second place, being them strictly dependent on the selected cultivars.
The choice concerning the crops to plant is made according to several criteria. The crop category, the specific cultivars and the extension of the allocated fields must be identified according to profitability, seasonality, logistical feasibility and many other factors that will be listed in the following Sections.
Cereals, legumes, fruits, vegetables, other edible (e.g. spices, sugar crops), non-food (e.g. energy, fiber crops) and industrial (e.g. tobacco, cotton) crops are the most common ones in temperate regions, but each of them shows peculiar needs and features, which must be accounted for in the decision-making process. Still, not only crop agronomic characteristics intervene in the decision-making process, but also their final use: for instance, conventional crops can be used for food or energy production purposes, but in the latter case alternative genotypes with lower nutrients and water demands can be used, resulting less expensive to crop (Zegada-Lizarazu and Monti, 2011).

A first crop-dependent factor influencing the crop choice is the *duration of the growing period*. Annual crops involve lower capital costs to be cropped and lower incomes, but are traditionally sold within a year of planting (Sims *et al.*, 2006). On the other side, perennial crop choices, such as orchards, do not produce economic yields until a few years after establishment: on one side, since they entail remarkable capital accumulation, they are also significantly more profitable than non-capital intensive crops as most of annual ones, but on the other hand farmers are exposed to risk of significant capital loss in the case of dry or negative seasons from a climatic viewpoint.
A few studies propose models to simulate how risk acceptance by farmers, quantified as cost of uncertainty, varies according to crop profitability, given a certain probability of losing the initial investment in multi-annual crops (Lavee, 2010). In addition, risks associated with potential changes in market are greater with perennial than with annual crops.
For other reasons, perennial crops are considered favorable to annual ones as establishment costs are reduced and soil chemistry and structure maintained (Sims *et al.*, 2006). In fact, rotation aimed at soil properties conservation is implemented

mainly with annual crops, whereas with perennial ones the rotation period is in the order of about 10 years, a too long time interval for farmers' to rely on rotation (Zegada-Lizarazu and Monti, 2010).

As just suggested, the choice about which crops to plant can also be made to restore the physical/chemical properties of the soil and ultimately its productivity, even though nowadays heavy applications of synthetic fertilizers, pesticides and other agrochemicals together with tillage practices are commonly chosen to compensate the soil properties deterioration and let farmers grow the same most profitable crop typology for many years on the same field. However, no amount of synthetic fertilizers and/or pesticides applied to a continuous monoculture system can completely compensate for the beneficial effects of crop rotations on crop yields, but many farmers still believe that monocultures represent the most profitable option (Zegada-Lizarazu and Monti, 2010).
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 diversified agricultural equipments and agricultural supplies which not all farmers can afford. Moreover, as compared to continuous monoculture systems, rotation can be expected to reduce the dependence on external inputs through promoting nutrient cycling efficiency, effective use of natural resources, especially water, maintenance of the long-term productivity of the land, control of diseases, pests and weeds, and consequently increasing crop yields and sustainability of production systems (*ibidem*), as will be further specified in Section 2.2.4. For example, introducing a legume crop in a rotation built around one or two leading crops (e.g. cereals) can improve the soil fertility because of legumes' atmospheric nitrogen fixation capabilities and addition of organic matter in the soil, since the roots of legumes remain in the soil at the end of the growing period (Sombrero and de Benito, 2010). The yields of the subsequent cereal crops can thus be increased significantly with lower chemicals applications (Ali and Talukder, 2008).
In addition, another relevant factor influencing the crop sequence selection is the roots length: deep-rooted crops such as sunflower, sorghum, rapeseed and hemp are best fitted to follow shallow-rooted crops because of their capacity to use water and nutrients that moved to deep soil layers during the previous season.
Therefore, site-specific decision criteria and climatic conditions affect the decision

about the best crop sequences. For instance, fallowing is used in rotation schemes to enhance their beneficial effects especially in Mediterranean climates of southern Europe where there are few alternative crops to include in a rotation as reported in the study by Zegada-Lizarazu and Monti (2010) by means of maps relating the climatic stratification of Europe (Metzger *et al.*, 2005) to the corresponding feasible rotations.

On the basis of all these factors affecting the crop sequence, farmers will then decide whether the reduction of chemicals application and increased sustainability of their agricultural system is worthy of alternating the most profitable crops with less profitable ones, as legumes or other rotation crops are.

Crops' profitability varies according to other agronomic factors. Among them, 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), thus crop choices must be made according to each farmer's water availability: for example, C_4 plants show a water use efficiency value two times bigger than C_3[4] ones, so they produce twice the harvest with the same amount of water; in addition, genetically-improved plants may prove to be more resistant to water stress (Ali and Talukder, 2008; Bindi and Howden, 2004) and allow improved yields and lower production, but in this case farmers' ethical inclination to genetically-improved crops plays a decisive role (Cardoso and James, 2011).

Water demand and stage-dependent sensitivity to water stress are relevant pieces of

[4] C_3 plants (95% of all the crops) flourish in temperate regions and are photosynthetically active during the day, whereas at night their stomata are closed thus only respiration takes place. Basically, they rely on the standard photosynthesis process, which becomes inefficient in hot climatic conditions because high temperatures lead to strong evaporations from stomata. C_4 plants (only 1%) as maize, sorghum and sugar cane instead inhabit regions with typically hot climates and have a very high water-use efficiency because they adapted to dry climates to save water in the carbon fixation phase of the photosynthetic process: this allows them to produce up to twice the biomass per gram of water than C_3 plants.

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 and management options (see Section 2.2.2).

Finally, crop typology is also influenced by some new trends involving the energetic field. In the last 10 years, the worldwide area dedicated to energy crops has increased tenfold and there is large consensus that the demand for energy crops will further increase rapidly to cover several millions of hectares in the near future (Zegada-Lizarazu and Monti, 2010).
Farmers' interest and attention towards the so called energy crops increased remarkably thanks to different factors: the increase in traditional fuels prices (and hence operating costs for trucks and tractors), the introduction of national incentives on energy production from renewable sources (which include biomass) and the adoption of national policies to meet the requirements of some recent European Directives[5] (use of 10% biofuels by 2020) led to a growing interest in alternative energy sources and in some cases to a partial shift of the crop production from food to energy generation purposes. In fact, among the available alternative energy sources that would help to respond to such challenges, biomass crops have many advantages over some other renewable energy sources as wind or photovoltaic, in particular because of its reduced dependence on short-term weather changes.
To quote some possible applications of energy crops, oil crops like rapeseed, sunflower and palm can be used directly as heating fuels or refined through transesterification processes to biofuels (such as biodiesel) for transportation purposes or energy generation in combustors. Use of crops for electricity generation is preferred to use of crops for transport fuels production since the latter scores low on both ecological and socio-economical criteria (Hanegraaf *et al.*, 1998). However, electricity generators entail remarkable initial costs that farmers cannot always afford whereas equipments for alternative fuel production are generally cheaper, even though profitability is lower in the long run.
Concerning other energy crops applications, sugar and cellulose crops starch can be used to produce ethanol by fermentation. The grains of cereals like wheat and maize can be used to produce ethanol and the straw can be used as a solid fuel; they can

[5]PE-CONS 3736/08. The European Parliament. Directive of the European parliament and of the Council on the promotion of the use of energy from renewable sources amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC; 2008.

also be grown and harvested as a whole crop (grain plus straw) before the grain has ripened and used as a solid fuel or for biogas production feedstock (Sims *et al.*, 2006).
An interesting and problematic trend has been happening in Italy in recent years: being maize highly profitable if used in biogas plants because highly energy-intense, from 2010 (when the first incentives were enacted) many farmers stopped producing maize for food purposes and used it instead in anaerobic digesters for biogas production. This shift significantly affected the market and price of maize in Italy, where biogas plants are granted the highest incentives all over Europe, until the government, to counteract the worrying trend, modified the incentives and differentiated them according to the feedstock used: crop residues, despite being less energy-intense, are now granted higher incentives than dedicated crops.
These are some examples out of the many applications of biomass use for energy production purposes. Further deepenings on conversion technologies and rotation principles can be found respectively in Sims *et al.* (2006) and Zegada-Lizarazu and Monti (2010).
In conclusion, farmers' planning about energy crop typology to plant, besides the factors listed at the beginning of the Section that affect every crop choice (conventional and energy crops), will also depend on the application they will be used for, on their energy-intensity if used directly in combustors or typology and quality of fuels that can be derived from them.

2.2.2 Irrigation technique

Irrigation technology

While crop choices can be easily arranged and modified even on a yearly basis according to the conditions and principles explained above, the decision to change the irrigation technique is quite challenging because of significant requirements in terms of time for the irrigation system conversion and capital involvement. Of course, the choice to upgrade irrigation structures and equipments 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 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 fixed 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. Lining of irrigation channel also involves a considerable amount of fixed costs (Ali and Talukder, 2008). In addition, the compatibility with the chosen crops is of paramount and self-explanatory importance: as a simple example, rice needs to be cropped with surface irrigation, even though alternative techniques are being tested to reduce the high water losses characterizing surface irrigation due to percolation or evaporation.

Other elements intervene in the decision about the irrigation typology to adopt: a recent study by Wang Xue-Yuan (2010) provides a statistical analysis of the estimated correlation existing between chosen irrigation techniques efficiency and different factors of interest, with more than 400 households located in China as source dataset. The results clearly indicate that age (generally proportional to production experience), education (and thus access to information on improved and most advanced technologies (Deressa *et al.* (2009)), household size and income (financial strength) are positively correlated to irrigation efficiency and thus adoption of more advanced irrigation techniques. On the opposite, the estimated correlation coefficient related to the cultivated area was negative, suggesting, as expected, that the wider the cultivated area, the greater the water losses by percolation in canals and fields.

Similar results were obtained by Deressa *et al.* (2009) focusing on the analysis of the determinants of farmers' choice of adaptation strategies to climate change in the Nile basin of Ethiopia, using, as numerical tool, a multinomial logit (MNL) model. The adaptation measures here considered are different crop varieties, tree planting, soil conservation measures, early and late planting, and irrigation systems upgrading. A positive correlation between age, education, household size, income and irrigation systems upgrading is shown as in Wang Xue-Yuan (2010), but adding some other interesting factors: males are in general more willing to invest in irrigation systems than females are, access to credit and information about the expected increase in temperature due to climate change also have a positive effect on this decision.

Besides the statistical analysis, the study by Wang Xue-Yuan (2010) also suggested, in accordance with the report by Ali *et al.* (2008), that the most traditional irrigation techniques, characterized by invariable irrigation time schedule and long distance of water delivery, have lower efficiencies than well, mix or drip (micro) irrigation, which instead show a high adaptability to the crop actual (i.e. stage-dependent) demand and reduction of water wastage in transport due to percolation and evaporation effects: experienced and wealthy farmers are thus likely to move towards the latter techniques.

Irrigation management

Besides the irrigation technology, irrigation management, in terms of annual volume supply and distribution during the growth cycle, influences the yields remarkably, because of its close relationship with the crop water demand and stage-dependent water stress sensitivity.
A technique that is becoming more and more widespread in the cases of limited water availability (or with the aim of decreasing water-related costs) is the *deficit irrigation* which consists in exposing crops to certain levels of water stress (namely keeping the soil moisture below field capacity) during either a particular growth period or throughout the whole growth season to reduce percolation and evaporation. Therefore, if water stresses are applied during low-sensitivity crop growth stages, substantial improvements in water productivity can be achieved because the plant is forced to use the water stored in the root zone without significant impair of crop yields (FAO, 2002)). Another reason that enhances the relevance of deficit irrigation programmes is that with a lower water supply, the leaching of nutrients, pesticides and fertilizers caused by water percolation decreases remarkably, reducing costs of fertilizers application and groundwater pollution as well. Deficit irrigation can be applied with two methods: reducing the amount of water applied or reducing the frequency by increasing the interval between successive irrigations. This can be practically accomplished by refilling only part of the root zone or only a fraction of the soil water field capacity of the root zone, wetting furrows alternately or placing them further apart (Ali *et al.*, 2008).
The relationship between irrigation management in terms of annual water volumes supplied to the crop and yield reduction in the cases of water deficit conditions has been extensively analyzed in literature. Some examples given by Greenwood *et al.* (2009) show that the Maximum Allowable average Deficit Percentage (MADP) dur-

ing the whole crop growth[6] is higher in cereals and forages, whereas for spinach and potatoes it is much lower, meaning thus a higher average sensitivity to water stress during the growth cycle of the latter crops. Therefore, as Ali and Talukder (2008) report, a study proposed by the International Center for Agricultural Research in the Dry Areas (Zhang and Oweis, 1999) has shown that application of only 50% of full supplemental irrigation requirements causes a yield reduction of only 10-15%. In addition, under the assumption of limited water availability (50% of the full irrigation required), Zhang and Oweis (1999) showed that a farmer with 4 hectares would, on average, produce 33% more grain if deficit irrigation is applied over the whole area compared to full irrigation over only part of it. Other studies show that in rice cultivation, instead of maintaining 3-5 cm standing water in the field, application of irrigation after 3-4 days of disappearance of ponded water leads to 20-30% water saving without significant yield reduction (Sandhu *et al.*, 1980; Pandey *et al.*, 1989; Sarkar *et al.*, 2002).

As previously anticipated, not only the absolute value of annual distributed water volumes (and the consequent average water deficits during the whole crop growth period), but also the irrigation distribution in time should be tuned according to time-varying crop needs, tolerance to water stress and field conditions, being these relevant factors affecting the biomass growth (Bindi and Howden, 2004). Two other noteworthy studies proposed by Tejero *et al.* (2011) and Greenwood *et al.* (2009) support the relevance of irrigation distribution in time and show that an equivalent amount of water applied to a field by means of different timing strategies - in terms of amount, frequency and crop growth stage - can promote different crop responses, and thus different effects on crop yields.
Specifically, Tejero *et al.* (2011) assessed the response of water use efficiency in citrus orchards at three different deficit irrigation strategies during three consecutive seasons (from 2006 to 2008). Sustained Deficit Irrigation (SDI) is based on the application of a certain degree of constant water stress throughout crop growth, without considering its phenological status or the accumulated water stress; Regulated Deficit Irrigation (RDI) tunes the water stresses duration and timing according to crop phenology and physiological stage; Low-Frequency Deficit Irrigation (LFDI) increases the period between successive irrigation cycles but keeps the water stress

[6] Expressed as a proportion of the available water to the depth of rooting (MADP(5)) and standardized to an ET of 5 mm/day (after Allen *et al.*, 1998)

below a crop-dependent threshold. As far as citrus (and fruit trees in general) is concerned, the results showed that SDI allowed the highest water saving but reduced the yield significantly, whereas a well tuned RDI (with stronger deficits applied during the maturity phase) allowed quite high water savings keeping the yield almost intact. LFDI showed the worst results: a strong yield reduction was not justified by the corresponding water saving, that was comparable to the one obtained with RDI.

Besides the dependency of the crop yield on the overall amount of water supplied to the plant, several studies attempted to assess the effects on crop yields of different irrigation management policies in terms of frequency and distribution in time (given a fixed annual volume supplied), by accounting for the crop stage-dependent sensitivity to water stress. Greenwood *et al.* (2009) collected some information from literature data and summarized the most sensitive growth stages for different crops, even though quantitative indications concerning the expected potential yield reductions as a consequence of water deficits were not provided. The study proposed by Ali *et al.* (2008) agrees that tolerance to water stress varies during the growing season and reports that generally a higher sensitivity characterizes flowering and seed development stages. According to Singh (1981), without prior evapotranspiration deficit in the vegetative stage, wheat yields were sensitive to water deficit during the critical booting/heading period but they were relatively insensitive when the plants were exposed to a 15% moisture stress in the vegetative stage. These findings suggest that the proper sequencing of water deficit reduces its detrimental effect on yield formation and hence increases water productivity.
A specific remark about grain crops sensitivity to water stress is due, being them very widespread in temperate regions. The fundamental consideration is that the economic value of these crops (e.g. in cereals) lies in the grain yield, not in the straw yield. Maize can be used as a quite illustrative example: its annual water demand is quite large and its peak appears in July and August, not only because of high temperatures and low precipitations (at least in temperate regions), but mainly because of the ongoing highly water demanding cereal grain development process. Ali *et al.* (2008) suggests that failing to supply enough water to corn plants in these months provokes a reduction of the duration of grain filling and thus final grain weight can result to be remarkably reduced, whereas water stresses in the earlier growth stages affect the final harvest less strongly. At the same time,

controlled soil drying during grain filling processes can enhance and speed up the whole plant senescence, causing an opposite effect: early senescence leads in fact to the re-mobilization of pre-stored carbon reserves in the straw and thus increases the grain biomass and harvest index (the marketable fraction of biomass, namely the grain biomass). Gains from the improved harvest index may outweigh any possible biomass loss due to shortened photosynthetic period in grain filling (Yang *et al.*, 2001). In agreement with these results, Zhang *et al.* (1998) reported that a soil drying during the wheat grain filling period enhances early senescence: while the grain filling was shortened by 10 days (from 41 to 31 days) in unwatered (during this period) plots, a faster rate of grain-filling and enhanced mobilization of stored carbohydrate minimized the negative effect on yield. Therefore, Ali (2006) found the highest harvest index and irrigation water productivity with alternate deficit treatment, with water shortages mainly happening during the grain filling stage. This result agrees with the findings of Liang *et al.* (2002), who demonstrated that the drying-rewatering alternation (alternate deficit) applied to wheat plants had a significant compensatory effect that could reduce transpiration but let the plant keep growing, with a significant increase of water use efficiency.
The experimental results just listed revealed that a certain amount of water deficit should be spread out over the whole growth period with alternate wetting and drying: this management policy, in fact, lets hardening processes take place, making plants less sensitive to renewed water stress thanks to osmotic adjustment processes in the leaves and leaf cells elastic modulus change (Turner, 2004).
One last factor influencing the irrigation management policy is represented by the selected crops' roots length: heavy and occasional applications of water are in fact advisable for deep-rooted crops, light and frequent instead for short-rooted ones, being the latter able to retain less percolating water (Zegada-Lizarazu *et al.*, 2010).

A final remark concerning the existing technologies able to enhance the irrigation management optimization seems relevant. In these recent years, advances have been made in understanding the soil-water-plant economy: at first, by the integration of this knowledge into simulation models; then by the improvement of sensor technologies to monitor soil water content; finally, by the introduction of wireless technology that can be used to transmit in real time sensor data in different locations at different depths to a central processor which guarantees a live control on irrigation intensity and frequency and an automatic control of irrigation equipments from remote.

Sensor-driven irrigation is becoming more and more widespread, especially in arid regions or where deficit irrigation programmes are applied, and allows a far better irrigation scheduling and significantly reduces water wastage. Nowadays, farmers generally rely on their past experience to schedule irrigation cycles, but this method is quite approximate and thus often provokes high water losses. Plant-based models can also be used, but require expertise for being difficult to operate and interpret. Thermal imaging is one of the most promising approaches and is based on measurements of the drop in temperature resulting from the evaporation of water, but shows a low reliability in humid regions and climates. Finally, soil water sensors can be used as alternative to micro-wave moisture estimation radar techniques and are being installed in more and more contexts because of their low price, simple operation and low labour requirement (Greenwood *et al.*, 2009).
There exist two different sensor typologies on the basis of the quantity they measure: soil water content and soil water potential. The majority of the former actually measures the dielectric constant of soil, which is largely determined by its water content. Although they do not always provide reliable measurements of soil water content, dielectric sensors are generally chosen where there is a requirement to measure small but rapid changes in soil water contents needed for precise control of water. On the opposite, sensors that measure soil water potential make use of a granular matrix that adapts to the soil water conditions and estimates the water potential by measuring the dielectric constant of the matrix. The main advantage is this sensor typology is represented by the low cost, durable reliability of 3 to 5 years (Qualls *et al.*, 2001) and their ability to work in small volumes of soil, whereas their main shortcoming is that they are slow to adapt to water content changes, limiting their use in dry areas (Greenwood *et al.*, 2009).

In conclusion, both irrigation technologies and management policies need to be tuned according to crop needs and features, farmers' capital and water availability. In the cases of low water availability, deficit irrigation proves to be a good compromise between crop yields maximization and water use minimization, provided that the deficit distribution in time is in accordance with the stage-dependent water stress sensitivity of the crop. In these situations, monitoring systems connected by wireless technology may improve significantly the overall irrigation efficiency and limit remarkably possible yield reductions due to excessive soil drying.

2.2.3 Fertilizers and pesticides application

Section 2.2.1 already discussed the relationship existing between the sequence of crop choices and possible agrochemical application reductions. As mentioned, in intensive agricultural systems as the Italian one fertilizers and pesticides are commonly used to increase crop yields since very frequently farmers prefer monoculture over rotational crop choices. 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 adding other crops in rotation is considered.

Fertilizers are mainly used to restore the balance of nitrogen and phosphorous content in soil and specifically to restore the well-known optimal ratios for plant growth and biomass production (with P reference concentration bigger than a crop-dependent minimum value, e.g. 30 ppm for winter wheat (Beurlein, 2001)

$$\text{C:N:P} = 100{:}10{:}1$$

These two elements, together with potassium, calcium, magnesium and sulphur are the basic mineral nutrients required for the plant photosynthesis process and thus biomass growth. However, plants' nitrogen and phosphorous demands and consumption are generally high and thus soils generally lack these two elements more than the others: for this reason they need to be restored, either by rotation or by fertilizers use. Therefore, fertilizers contribute to above ground biomass synthesis and yield development not only directly, namely by fostering the photosynthesis process, but also indirectly, because they facilitate roots development and consequently enhance the ability of crops to absorb water and other nutrients stored in deeper soil layers. However, some studies suggested that there exists a certain crop and soil dependent threshold beyond which no further beneficial effect appear (Ryan, 2000; Ali and Talukder, 2008).

As concerns pesticides, their use became common as an alternative to mechanical methods of pest control like tillage or altered harvesting practices that will be described in more detail in Section 2.2.4. The shift from mechanical to chemical methods was strongly favored when research proved the existence of a connection between field erosion phenomena and lack of soil cover due to the implementation of mechanical methods of pest control: these, in fact, aimed to remove as much plant

residue from the field as possible so that pests had no food source to sustain them until the next growing season.
Pesticides are toxic substances by design, and their spreading elicited a natural concern about their presence in the environment on human health and environmental quality. However, farmers' choice on the pesticide typology to use fundamentally depends on the pests that mostly affect the crop.
At the same time, another relevant aspect involving both fertilizers and pesticides choices is the following: their fate and transport in the environmental matrices are governed by different properties such as volatility, ease of degradation (photodegradation, biodegradation and chemical degradation) and solubility in water, which influences the wash-off from plants, removal from the superficial soil layers due to runoff or leaching processes during rain events or irrigation cycles (SWAT manual, 2011). The choice on the fertilizer and pesticide typology must then be taken also according to these features, which influence the frequency of interventions to restore the desired conditions, along with their compatibility with the chosen crops.

2.2.4 Best Management Practices

Besides the most traditional management activities and choices listed and detailed in the previous Sections, the most environmental-friendly and far-seeing farmers are starting to get accustomed to solutions aimed at environmental preservation and sustainability. The implementation of Best Management Practices (BMPs from here on) can minimize the potential of agricultural non-point source water pollution and other adverse environmental and social problems. BMPs are practices based on the most recent available research and scientific data and their combination permits efficient farming operations and optimum forage and crop yields, while achieving the least possible adverse impact upon the environment or human, animal and plant health by minimizing the use or mobility of fertilizers and pesticides (Agricultural Best Management Practices Task Force, 2002). Besides the obvious goal of avoiding excess in fertilizers and manures applications beyond the real crop needs, BMPs are aimed at accomplishing three basic and relevant purposes that are here just mentioned and then will be treated in more detail in the following Sections:

- minimization of water losses due to evaporation or percolation to reduce water demands and consumption;

- minimization of herbicides and insecticides application through pest management strategies based on the understanding of the biological features of target pests and use of a combination of physical, chemical, biological and cultural controls;
- finally, the control of soil erosion and runoff processes, which are respectively responsible for soil quality degradation and transport of fertilizers and pesticides to superficial water bodies or groundwater, can be attained by means of mulch covers or residue management strategies like conservation tillage.

The decision-making problem aimed at BMPs selection is rather complex and involves different aspects, as shown by the scheme represented in Figure 2.2. Very synthetically, starting from farm, environmental, economic and other objectives, an analysis and evaluation of the feasibility and expected impact of each possible BMP in each specific case is carried out and finally the set of optimal activities is chosen according to the considered objectives.

Going into the details of the most common BMPs, a range of water conserving practices is frequently used to reduce water losses and thus decrease irrigation operating costs, as well as combat droughts or reduce climate change impacts (Easterling *et al.*, 1996). Such practices include optimized irrigation management, mulch cover and conservation tillage.
As previously treated in Section 2.2.2, *irrigation management optimization* improves considerably the efficiency of utilization of applied water through proper timing of the water distribution. For example with modern irrigation scheduling practices and soil monitoring technologies, irrigation cycles can be applied only when needed by the crop. This permits to tune the proper timing and amount of water to actual field conditions allowing consequently a reduction in water use and cost of production.
Mulch covers are frequently chosen to reduce runoff during intense rainfall events and hence the nitrogen removal by runoff or leaching. Mulching also increases water retention and reduces evaporation, reducing the demand for irrigation water and thus related leaching effects (Ali and Talukder, 2008; FAO, 2002).
Conventional tillage is instead the practice of leaving some or all the previous season's crop residues on the soil surface. This may protect the soil from wind and water erosion and retain moisture in the subsoil, by reducing evaporation and increasing infiltration of precipitations (Bindi and Howden, 2004; Howden *et al.*, 2007; Ali and Talukder, 2008). A well-documented drawback of this technique is the difficulty to

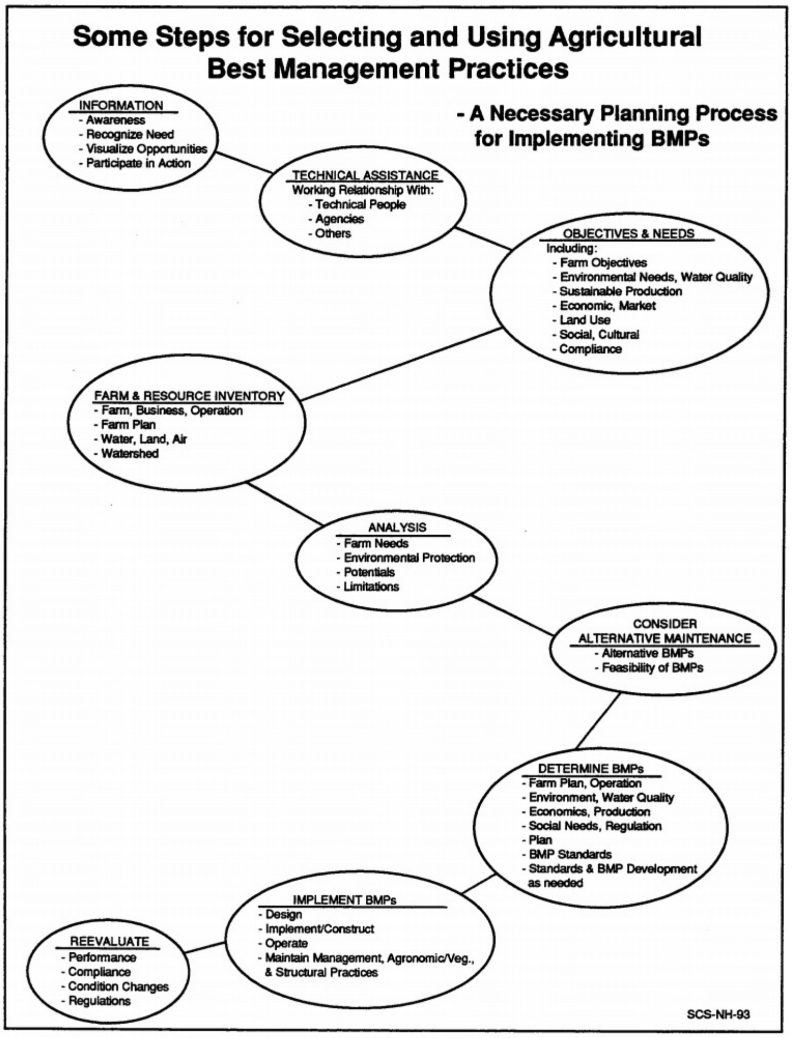

Figure 2.2: The phases of the BMPs planning problem (US Agricultural Best Management Practices Task Force, 2002).

control pests that feed on the crop residues left on the field: this issue led, as already reported in Section 2.2.3, to a strong increase in chemical applications to counteract pests growth and spreading. Nevertheless, in order to enhance the sustainability of agricultural systems, a good balance between pest control and soil erosion avoidance should be sought. Both are in fact necessary to increase crop production but potential environmental impacts should be accounted for and carefully evaluated, along with purely economic criteria.
Also the quantitative effects of different tillage strategies (no tillage versus conventional tillage) on soil hydraulic properties and processes should be considered (Strudley *et al.*, 2008) because they have a strong influence on the chemical transport phenomena (and thus the likelihood of agriculture-derived pollution in water bodies) and plant growth (and thus agricultural productivity). The strong heterogeneity of the results of the studies reported proves that the effectiveness and impacts of tillage practices are too site-specific to draw some general conclusions.
In addition to the aspects related to soil erosion reduction and difficulty in pests control, an interesting study by Sombrero and de Benito (2010) analyzes the relationship between different tillage practices (no tillage, minimum tillage and conventional tillage) and the soil organic carbon (SOC) content. Increases in the SOC pool improve soil structure, counter soil erosion, raise water capacity and plant nutrient stores and improve the harvest index (Lal, 2007). By minimizing soil disturbance, *conservation tillage practices* (minimum and no-till) have been observed to decrease the mineralization of organic matter leading to a larger store of SOC than with conventional tillage (West and Post, 2002; Al-Kaisi and Yin, 2005). On the other hand, conventional tillage is used to mix topsoil to recover nutrients in deeper soil layers, prepare the seedbed and control weeds, but has been associated with losses in soil organic carbon, which lead to a significant decline in soil quality in the long run (Hernanz *et al.*, 2002). However, in contexts where water availability does not represent a limiting factor, conventional tillage proved to allow a larger biomass production than minimum tillage or no tillage. This is the main reason (others are the soil erosion reduction and moisture containment) why conventional tillage is generally preferred to conservation tillage, requiring, as a consequence, heavy applications of pesticides to counter pests growth.

In the category of BMPs also some crop choices principles can be included. The main factors affecting crop choices are dealt with in Section 2.2.1, but it is worth noting

some further aspects related to agriculture-derived pollution reduction. Fertilizers reduction can be accomplished with the introduction of legumes in crop rotation plans (see Section 2.2.1). As concerns pesticides, the use of crop varieties and species resistant to pests and diseases could improve the effectiveness of pest, disease, and weed management practices and reduce, at the same time, the pesticides demand, use and thus the environmental impact of crop production (Howden *et al.*, 2007). In literature, various studies agree that the combination of crop rotations with cover crops and reduced or no-tillage practices can further improve soil physical, chemical and biological properties, reducing in this way pesticides need (Gebremedhin and Schwab, 1998; Peel, 1998; Zentner *et al.*, 2002).
Crop rotation plans should take into account the effects that different crop sequences have on pests such as weeds, insects, and diseases. Francis and Clegg (1990) indicated that the more diversified the cropping sequence the better the control of pests. However, rotations with food and/or energy crops cannot control all kind of pests. In fact the range of pest that are best controlled by crop rotations are circumscribed to those that are soil/stubble born nematode/pathogens with limited mobility and cannot survive long periods without a living host plant (Bullock, 1992; Karlen *et al.*, 1994). Deep knowledge of crop diseases and their management practices are then necessary in order to design successful rotations aimed at pests and diseases control without or with minimum chemicals application. The life cycle and survival time of a pathogen without a suitable plant host is a major factor that plays an important role in determining the frequency of a crop in the rotation. Thus, alternating crops with contrasting characteristics, between them and with those of the predominant weeds, is a successful strategy (Robson *et al.*, 2002).
Therefore, including particular crop species may reduce pesticides requirements: for example, allelopathic crops may inhibit, to some extent, weeds growth (Mamolos and Kalburtji, 2001); sorghum, sunflower and hemp are some examples of energy crops that produce phytotoxic compounds that could act as herbicides (Einhellig and Rasmussen, 1989; Funnel-Harris *et al.*, 2008). On the other hand, strong knowledge about these effects is required and careful planning is necessary, because in some cases the phytotoxic effects of some crops may be not only poisonous for weeds but also for the following crops (Zegada-Lizarazu *et al.*, 2010).

Not only crop typology and sequence, but also other farming BMPs involving *sowing and harvesting strategies* can contribute to enhance water use efficiency (Bindi

and Howden, 2004) and decrease agrochemicals applications thanks to a naturally improved pests control and more efficient nutrients absorption: the environmental impact is thus minimized, while, at the same time, the final yield and thus revenues are maximized.
In agriculture, *multiple cropping* is the practice of growing two or more crops in the same fields during a single growing season. All over the world, multiple cropping has been applied using strategies that differ from one another in terms of degree of crops' spatial and temporal overlap (Andrews and Kassam, 1976). Producing a second crop allows for the increased use of machinery, labor, and land during the year and a lowering of fixed cost on a per-hectare basis, resulting in a more profitable farming operation (Beuerlein, 2001).
The three most common applications of multiple cropping are known as double, relay and inter cropping.

- *Double cropping* is the practice of planting a second crop just after the first has been harvested: for instance, winter wheat and short-cycle maize can be cropped in the same year, maximizing the revenues and reducing the water demand during summer.

- *Relay cropping*, instead, consists of interseeding the second crop into the first crop well after it is sowed and before it is harvested. This technique enables the production of a second crop in areas where the available time for the growth of a second crop sowed after the harvesting of the first is inadequate (too short), but limiting as much as possible the temporal overlap of the two crops in order to minimize the spatial competition: the first crop is in fact harvested to make room for the full development of the second.

- *Intercropping* is finally the practice of growing two or more crops in proximity, and specifically sowing in the same moment an additional crop in the spaces available between the rows dedicated to the main crop.

Some noteworthy relationships exist between these three alternatives and water and nutrients demands. In general, multiple cropping entails a higher water demand, but when temporal overlap takes place as in the cases of relay and intercropping, crops make use of resources that would otherwise not be utilized by a single crop, bringing about increases not only in total crop yields, but also in water use and nutrients absorption efficiency. As a matter of fact, water volumes located in the spaces between the rows of the main crop would be lost by percolation or evaporation, and nutrients by leaching or due to runoff processes. Instead, in the case of double cropping, in which no temporal overlap exists, the annual average water demand is intuitively higher than in single-crop systems, but it is more efficiently distributed during the year. This distribution leads to lower water demands during summer, whereas during winter water requirements are almost completely covered by rain events (at least, in temperate climates). Thus, the overall amounts of water that must be distributed with irrigation cycles during the year turns out to be comparable to single-crop systems'.

However, careful planning taking into account crop varieties and soil and climate conditions is required. It is particularly important not to have crops competing with each other for physical space, nutrients, water, or sunlight. Examples of successful intercropping strategies are planting a deep-rooted crop with a shallow-rooted crop to avoid water and nutrients competition, a tall crop with a shorter crop that requires partial shade or a fast growing crop with a slow growing one so that the former is harvested before the latter starts to mature. Other benefits can be obtained by structurally weak crops if coupled with higher and more robust ones in climates where winds or rainfall events are strong (Trenbath, 1976). Intercropping of compatible plants also favors biodiversity by providing a habitat for a variety of insects and soil organisms that would not be present in a single-crop environment. This biodiversity can in turn help to limit outbreaks of crop pests (Altieri, 1994) and reduce pesticides needs, fostering the environmental sustainability of the agricultural systems, as well as reducing the costs of agrochemicals applications.

2.3 Environment-dependent factors affecting farmers' choices

The optimization process that leads farmers to determine the optimal set of decisions to take for the coming year needs to account for factors, i.e. disturbances, which lie beyond farmers' control. This Section provides a few further remarks concerning hydro-climatic and socio-economic disturbances that were already mentioned at the beginning of this Chapter, in order to complete the framework of FDMP.

2.3.1 Water supply uncertainty

For the aims and purposes of this dissertation, a fundamental factor affecting farmers' choices is the uncertainty related to the water supply during the year. It is quite obvious that water scarcity should induce farmers to under-irrigate some crops with respect to the corresponding full potential evapotranspirative demand. In fact, reductions in yields may be proportionally less than reductions in water applied, being the relationship between water supply and crop yield non-linear (Ali and Talukder, 2008). However, this strategy increases water use efficiency and thus reduces irrigation-related operative costs, as discussed in Section 2.2.2 with reference to deficit irrigation programmes. However, when water availability (and hence evapotranspiration) falls below a certain point, the final profit gained from the crop can fall to zero either because the crop actually dies, or because the product (grain, cotton, or whatever) is of such low quality as to be unmarketable. The rationale for this is that output quality is higher if optimal yield values are achieved (Perry and Narayanamurthy, 1998). This possibility implies that a strategy of deficit irrigation, when irrigation supplies are uncertain, increases the risk of financial loss. There is thus a theoretical tradeoff between deficit irrigation and uncertainty of supplies.

Let us take, as an example, the already mentioned study of Zhang and Oweis (1999). Just to recall, their results proved that, under the assumption of limited water availability (50% of the full irrigation required), a farmer with 4 hectares would, on average, produce 33% more grain if deficit irrigation is applied over the whole area compared to full irrigation over only part of it. But this is an *a posteriori* reasoning, based on the knowledge of the realization of the uncertain water availability. At the beginning of the year, in fact, when farmers are expected to plan their activity in the coming months, they cannot predict what the water availability will be. Thus, the choice of applying strong deficits over a bigger area entails the risk of complete crop failure if there is a shortfall of water, from whatever source, in relation to expectations. On the other hand, if supplies are unexpectedly plentiful, extra water can be productively used to increase net returns, since crops will benefit from further water supplies.

In order to reduce the risk of complete capital loss, farmers may reduce the irrigated area and hence increase the amount of water applied per unit land. In this case, the possibility of shortfalls in supply is a less-serious threat: evapotranspiration can fall significantly, with significant but not disastrous yield reductions. On the opposite, unexpected extra supplies are less well utilized since evapotranspiration

cannot exceed the potential one so no significant extra benefits will be possible. As Perry and Narayanamurthy (1998) suggest, the potential profitability of pursuing deficit irrigation is modified by the inherent risk of the approach. While conditions of water scarcity induce farmers to practice deficit irrigation, the choice concerning the degree of deficit will be therefore strongly affected by the perceived reliability of supplies. This, in turn, is influenced by some objective reasons like the different climatic patterns, the difference between expected and actual water supply in the previous years and rainfall and temperature forecasts for the coming one. However, some subjective features intervene as well, since farmers' experience and risk aversion play a crucial role while dealing with water supply uncertainty.
If, however, an interaction and information exchange between farmers and Regulators was actually created, the uncertainty of the water supply could be strongly reduced and farmers' choices more likely to be successful.

2.3.2 Water price

In some cases, water prices may influence farmers' decisions as well. In fact, all over the world observed prices fluctuate widely, depending on the source (surface, groundwater, desalinization, recycled water, etc.) and the pricing policies in each region. The latest statistical data show water prices close to 0.04 $euro/m^3$, on average, although they may be nearly 0.11 $euro/m^3$ in the case of groundwater or regions with limited water availability (Pérez *et al.*, 2010).
An interesting study by Mejias and Varela-Ortega (2003) tested the influence of three water pricing policy options on farmers' behavior within the framework of the Common Agricultural Policy (CAP), reformed by Agenda 2000[7]:

- CAP reform of 1992 guarantees high price support because of low direct payments tied to crop yields;
- Agenda 2000 guarantees low price support because of high direct payments tied to crop yields;

[7] The aim of the Agenda 2000 CAP reform is to foster a multifunctional, sustainable and competitive agriculture throughout the EU territory. Based on the establishment of production-related direct aid payments, this reform gives a prominent role to agri-environmental instruments to support a sustainable development of rural areas and to respond to society's increasing demand for environmental services.

- Equal Aid Payment guarantees low price support because of the establishment of equal direct payments for all crops decoupled from crop yields.

This last scenario represents the trend followed by EU policies towards production-neutral payments and it can be considered a first step to the complete decoupled payments envisaged in the recent midterm review of the CAP.
The results of the study show that in all agricultural policy scenarios, farmers' water demand in water scarcity scenarios is not flexible at all, proving a strong rigidity to reduce water consumption unless operational costs get too high. In fact, water use during dry periods is not significantly reduced until prices reach high levels: Agenda 2000 shows the most inelastic demand as prices have to mount to 0.13 $euro/m^3$ to have significant decreases in water consumption, as compared to 0.11 $euro/m^3$ in the 1992 CAP scenario and 0.09 $euro/m^3$ in the Equal Aid Payment scenario, which then proves to be the best policy option to induce water savings (remarkable reductions can be attained without increasing the water prices too much). On one side, crops with low water requirements are consequently more and more cultivated in the irrigated lands. Thus, a crop specialization towards wheat production will be induced, whereas other highly water-demanding crops such as corn and sunflower will tend to disappear. On the other side, the implementation of an Equal Aid Payment Policy will attain the objective of water conservation and farmer's income preservation more efficiently than the other policy alternatives.
In this policy scenario, water is reduced without inflicting any income loss to the farmers who in fact attain a slightly higher income. In the other policy options water conservation objectives are only met at the cost of incurring in farm income reductions.
With reference to the relationship between water price and irrigation management, a recent study by Tejero *et al.* (2011) analyzes the variation of the economic profitability of deficit irrigation programmes with respect to water prices variations. As reported at the beginning of the Section , water price is frequently around 0.04 $euro/m^3$. The results of this study show that if the water price is very low, it is basically almost negligible in the economic balance and thus any deficit-irrigation strategy under these conditions would not be viable in purely economic terms. However, these prices often do not correspond to the real ones in conditions of water scarcity. Therefore, even in the regions where water costs are actually so low, the situation could change in the coming years, since current water price policies were implemented as a result of the application of the European Water Framework Di-

rective (EWFD, 2000) and thus rising water costs could be imposed in order to force improvements in current irrigation strategies. For example, with respect to full irrigation, RDI-4 (RDI in the fourth and last crop growth stage, see Section 2.2.2) would show a better balance between water costs and yield reductions if the water price rose to 0.35 $euro/m^3$; in the case of LFDI, which guarantees strong water savings but entails remarkable yield reductions, this treatment would not be profitable unless the water price rose to 1.09 $euro/m^3$ (a not realistic price, even in the worst conditions). In conclusion, water prices per m^3 are currently insignificant, and water savings are not reflected in greater profits, because the income losses from lower yield are not offset by the savings in the irrigation costs. However, if water prices rise in the future, water-saving techniques will translate into greater profits (Tejero *et al.*, 2011).

2.3.3 Other economic factors

There exist a series of uncertain variables that influence farmers' choices in addition to water prices or supply uncertainty.

At first, crops *sale price* plays a decisive role, being this the primary term that builds up the profits. However, when farmers plan their activity, namely take all the decisions listed in Section 2.2, they are aware of the crop prices in the previous year or years and thus they can deduce some trends if these are quite clear. Still, they have no guarantee about the crop prices in the following year, namely when they will sell the harvest. They can rely on forecasts, but – no matter what – their decision will be taken in uncertain conditions. Forecasts can be related to crop sale prices, crop demands on the market, bank interests on loans, and a large number of random inputs actually influence these variables. For instance, if the incentives on energy production from biomass sources are renewed and decreased only slightly in the coming year (they always have a decreasing trend until the so-called *grid parity* is achieved) it is reasonable to expect a good market demand for energy crops and thus good revenues. However, incentives for the coming year are not necessarily known when farmers plan their crop production, thus if the new incentives are much lower than forecasted, the energy crop profitability may drop suddenly.

Many other examples could be provided to support the strong relevance of economic trends and variables on crop production activities. However, in order to include these aspects in the numerical analyses of the following chapters, they would need to be studied in detail and these aspect go beyond the aim of this work. Models correlating economic trends (e.g. the crop price) and the variables that affect them (e.g. the annual crop production, namely the market supply) could be used to find some patterns linking them which could be added to improve the model that will be formalized in Chapter 3.

Chapter 3

Problem formalization

Chapter 2 outlined the structure and characteristics of FDMP from a qualitative standpoint. The main goal of this Chapter is to formalize the Coupled Model from an analytical point of view. Specifically, Section 3.1 is intended to describe the principles and methodology through which the integration between FDMP and WSMOP was accomplished. A pseudo-code will be also introduced to clarify the concepts. Each single problem will then be formalized and described separately: Section 3.2 provides the mathematical formulation of FDMP and describes the Crop Growth Model that was developed in this work to evaluate farmers' objective function; Section 3.3 summarizes the main concepts concerning WSMOP, without delving into the details, being the problem formulation and resolutive algorithm quite standard and extensively treated in literature. Finally, Section 3.4 describes the methodology that was implemented to generate the hydro-climatic scenario in forecasted climatic conditions: the time series obtained in this way will be used to assess climate change impacts on FDMP and WSMOP and the effectiveness of farmers' and Regulators' adaptation strategies.

3.1 Connection between FDMP and WSMOP: the Coupled Model

The main goal of this Section is to formalize the methodology developed in this work by introducing and explaining the algorithm which it is based on.

Just to recall, the main challenge that this work aims to tackle is represented by the activation of an information loop to integrate two different but interdependent decision-making processes, modeled as FDMP and WSMOP.

WSMOP

The Water Supply Management Optimization Problem consists in an off-line optimization of the water supply policy from upstream reservoirs. The Decision Maker is represented by the Regulator, namely the authority that is in charge of deciding the optimal daily releases from the reservoir. In this work a single Regulator is assumed, but in the case of complex water systems with different reservoirs, the Regulators could be multiple. The decisions on the daily releases are taken on the basis of some objective functions $\mathbf{J}^S$ which generally include, at least, the minimization of flood risks J^f (flood objective) and water deficits J^i (irrigation objective), see Section 3.3. This latter objective function is considered overriding in this work, since it shows the link existing between WSMOP and FDMP, on the basis of which the two problems can be integrated. The input to the WSMOP is the expected water demand of downstream users, namely the irrigation districts: other stakeholders as hydropower plants are disregarded since they are not the focus of this work. The output of the optimization process is the optimal operating policy given a certain expected water demand.

FDMP

Farmers' Decision-Making Problem consists in a simulation-based optimization which allows farmers to determine the optimal land allocation to each crop typology. In this case, the Decision Makers are multiple and are represented by each farmer belonging to downstream irrigation districts. Farmers can be modeled as rational, selfish and autonomous agents acting in a Multi-Agent System (MAS), which coincides with the irrigation district itself.
Given the expected water availability, farmers determine the land allocation to each crop by solving a yearly planning problem which allows them to identify the most profitable crop to plant: in this work, farmers' objective function J^F is the maximization of the revenues deriving from the end-of-year sales of the chosen crops.

Given the optimal crop choice, the water demand for the coming year can be estimated.
Irrigation districts are composed by different irrigation units, each of which receives a fixed share of the amount of water appointed to the irrigation district it belongs to (at least in rotational irrigation systems, which are very common in Italy). Turnovers define the distribution of water at each time step within the irrigation unit to each cell (i.e. field), with only one exception: cells in which crops are experiencing water stresses are the first to be irrigated. This consideration allows to show that the timing and amount of water that each cell receives (and consequently the water stress that each cell may be subject to) at a certain time instant depends not only on the crop typology chosen for that cell, but also on the water demand of crops planted in the other cells of the same irrigation unit (see Section 3.2.1 for further details). Due to the existence of a state-dependent rotational rule, the evaluation of the profitability of each crop would requires to test all possible combinations of each crop in each cell, or, better, to implement some advanced optimization algorithms (e.g. genetic algorithms), which, however, go beyond the aims and purposes of this thesis.
In order to make the simulation-based optimization feasible, the dependence of water stresses on the other chosen crops in the same irrigation unit had to be removed: it was thus assumed that each farmer (agent of the MAS) coincides with one irrigation unit, which receives a fixed share of the water withdrawn for its irrigation district and is allowed to choose only one crop typology. The independence of the water supply granted to farmers belonging to different irrigation units allows them to make independent choices and thus choose different crops. In the following, the terms "farmers", "agents" and "irrigation units" will be used as synonyms.

Integration of WSMOP and FDMP

The exchange of information between farmers and Regulator should be carried out at the beginning of each year in an iterative way until convergence between expected supply and irrigation demand is reached. Here follows the pseudo-code describing the algorithm that accomplishes the integration between WSMOP and FDMP.

The Coupled Model

1. *initialization*:
   $k = 0$
   $k_{max} = max_{iter}$
   $flag = 0$
   $W_t^{*k} = \hat{W}_t$
   $k = 1$
   hydro-climatic scenario, socio-economic scenario

2. BEGIN *information loop*
   (W_t^{*k-1}, hydro-climatic scenario) $\rightarrow$ WSMOP $\rightarrow r_t^{*k}$
   if "convergence is reached" $flag = 1$
   if $flag = 1$ or $k = k_{max}$ then RETURN r_t^{*k} and W_t^{*k}
   else $k = k + 1$
   (r_t^{*k}, hydro-climatic scenario, socio-economic scenario) $\rightarrow$ FDMP $\rightarrow W_t^{*k}$
   END *information loop*

In the above pseudo-code the meaning of the notation is the following: k represents the number of the current iteration, max_{iter} the number of maximum iterations, which can be set arbitrarily, after which the algorithm ends even though convergence is not reached, $flag$ is null until convergence in not achieved, W_t^{*k} identifies the water demand arising from farmers' optimal choices, $\hat{W}_t$ represents the historical water allowance of the irrigation district and r_t^{*k} indicates the optimal releases. The same notation is used in Figure 3.1, where a graphical representation of the reasoning on the basis of this work is provided.

It is useful to explain in words the meaning of the algorithm above. In the first iteration $k = 1$, the Regulator optimizes the reservoir operating policy on the basis of the historical water allowance of the downstream irrigation district (boundary condition in the *initialization* step). At the k-ith iteration, the optimal operating policy r_t^{*k} is determined by the WSMOP. Given r_t^{*k}, farmers optimize their decisions, i.e. crop topology, in order to maximize their expected income. Given the final crop choice in each irrigation unit, the real water demand W_t^{*k} of the whole district can be estimated.

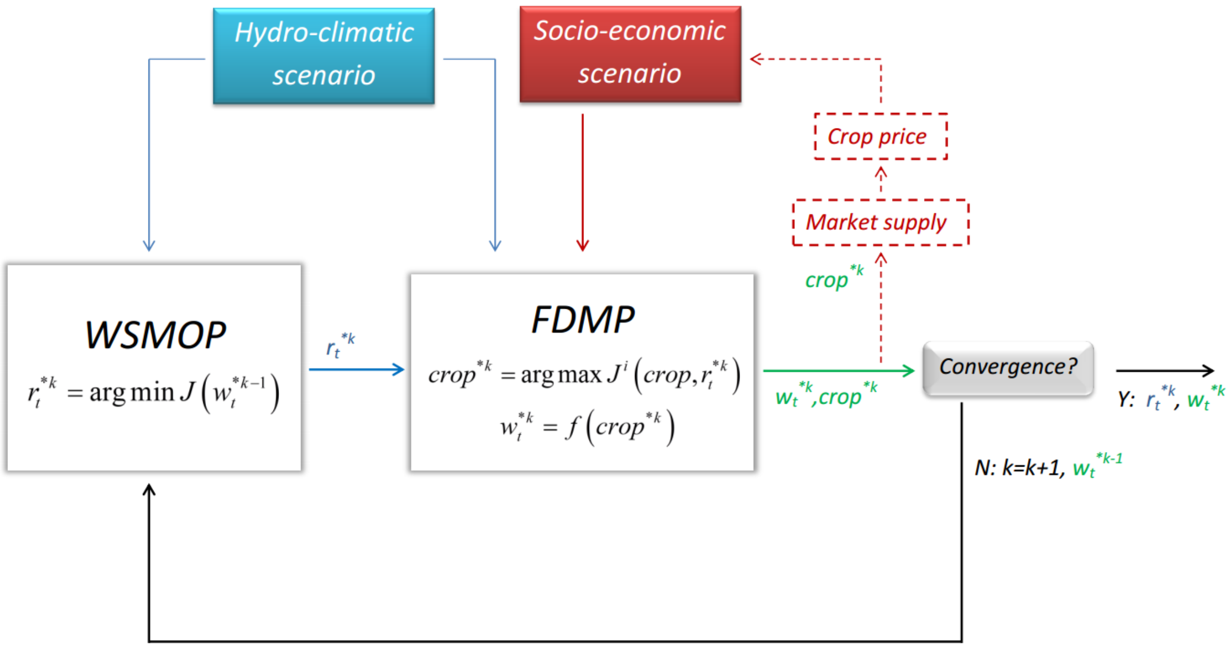

Figure 3.1: Scheme representing the reasoning on the basis of the Coupled Model: the variables that allow the integration between FDMP and WSMOP are highlighted.

The loop will be iterated until some convergence criteria are met or until an arbitrary maximum number of iterations is reached. As visible from the pseudo-code, the convergence criterion is evaluated at the end of the WSMOP, following the natural hierarchy of water systems in which farmers adapt their choices to the expected releases. Once the convergence condition is met and thus the optimal policy r_t^{*k} has been determined, farmers can optimize for one last time their decisions, following the traditional hierarchy in which farmers adapt their choices on the basis of the expected release.
Two possibilities are considered to express the convergence criterion.

1. Iterations can be stopped when the yearly district-level water deficit (i.e. computed in the whole district during the whole time horizon) is lower than a fraction – which can be set arbitrarily – of the water deficit deriving from the optimization of the operating policy based on the historical water allowance $\hat{W}_t$: this means that it is possible to stop iterations when the desired water deficit reduction is accomplished.

2. The second convergence criterion stops the iterations when the number of irrigation units allocated to different crops between two consecutive iterations is lower than a desired fraction of the total number of cells of the space domain.

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 implies a deficit minimization and does not consider the crop choice. Therefore, consecutive iterations may not achieve improvements in deficit results because of the possible existence of structural deficits. However, even an optimal policy might produce significant deficit which, consequently, do not guarantee the convergence of the loop. In addition, the second criterion is directly dependent on farmers' behavior and choices, which are the focus of this work. For all these reasons, the second criterion was adopted in this study.

Multiple irrigation districts

In real world situations, water systems rarely include a unique irrigation district. In the WSMOP, the optimal operating policy r_t^{*k} of the artificial reservoir is thus determined on the basis of the total downstream water demand

$$W_t^{*k-1} = \sum_i^{n_i} W_{i,t}^{*k-1} \tag{3.1}$$

where $W_{i,t}^{*k-1}$ $(i = [1, \ldots, n_i])$ are the expected water demands of the n_i irrigation districts at the previous iteration and are obtained by solving FDMP for each district.
As concerns FDMP, in the case of multiple irrigation districts, the actual water supply $Q_{i,t}^{S*k}$ that each district i receives is only a fraction of r_t^{*k} and is defined by case-specific sharing rules. In conclusion, multiple irrigation districts can be considered as different and connected MAS. However, this work is focused on building a methodology to integrate WSMOP and FDMP: the extension to multiple irrigation districts requires further investigations and could be the subject of future developments of this work. Thus, in the following formalizations, only one irrigation district is considered and consequently the water supply is defined as follows:

$$Q_t^{S*k} = f(r_t^{*k}) \tag{3.2}$$

where the function f is defined as in eq. (3.22) and does not account for sharing rules, being the irrigation district unique.

External driving forces

As Figure 3.1 shows, FDMP and WSMOP are influenced by exogenous inputs of two natures, hydro-climatic and socio-economic.
As concerns the hydro-climatic scenario, two possible options were considered in this work: on one side, the current climatic scenario, which can be built from the time series measured by the meteorological stations located in the study area; on the other side, the projected climatic scenario in the time period 2071-2100, which can be generated by means of the downscaling procedure, as will be discussed in Section 3.4. The use of two hydro-climatic scenarios allows to assess the potential impacts of climate change on WSMOP and FDMP and the effectiveness of adaptation strategies that farmers and Regulator may implement.
As concerns the socio-economic scenario instead, a fixed sale price was considered for each crop both in current and projected climatic conditions. As already discussed in Chapter 2, this represent a strong limitation to the approach: the market

sale price formation problem was not modeled for reasons of space and time, let alone its projection in the future. However, it should be reminded that this work aims to build a methodology to couple WSMOP and FDMP, as well as assessing its potential effects in climate change conditions: further modules could be easily implemented above the foundations given by this work.

3.2 FDMP formalization: a recursive planning problem

Unlike usual planning actions which are generally taken once and for all (e.g. the upgrading of the irrigation technique), farmers' business requires them to take some planning decisions periodically, e.g. on a yearly basis at the beginning of each growing season. However, farmers can also implement management actions during the year and hence, in order to evaluate the performance of each planning action and solve the Planning Problem, also the management policy must be optimized by solving an Off-Line Control Problem (Soncini-Sessa *et al.*, 2007). FDMP is thus composed by a cascade of planning and management problems:

The Planning Problem:

$$J^{*F} = \max_{\mathbf{u}^{pF}} J^{*F}(\mathbf{u}^{pF}) \tag{3.3a}$$

$$\mathbf{u}^{p*F} = \arg\max_{\mathbf{u}^{pF}} J^{*F}(\mathbf{u}^{pF}) \tag{3.3b}$$

subject to

$$\mathbf{u}^{pF} \in \mathcal{U}^{pF} \tag{3.3c}$$

The Off-Line Control Problem:

$$J^{*F}(\mathbf{u}^{pF}) = \max_{p^F} E_{\{\varepsilon_t^F\}_{t=1,\dots,h}} \{\sum_{t=1}^{h}[g^F(\mathbf{x}_0^{h,F}, \mathbf{u}^{pF}, \mathbf{u}_0^{h-1,F}, \mathbf{w}_0^{h-1,F}, \boldsymbol{\varepsilon}_1^{h,F})]\} \tag{3.3d}$$

subject to

$$\mathbf{x}_{t+1}^F = f_t^F(\mathbf{x}_t^F, \mathbf{u}^{pF}, \mathbf{u}_t^F, \mathbf{w}_t^F, \boldsymbol{\varepsilon}_{t+1}^F) \;\; t\text{=}0,1,\dots,h\text{-}1 \tag{3.3e}$$

$$m_t^F(\mathbf{x}_t^F) = \mathbf{u}_t^F \in \mathcal{U}_t^F(\mathbf{x}_t^F, \mathbf{u}^{pF}) \;\; t\text{=}0,1,\dots,h\text{-}1 \tag{3.3f}$$

$$\boldsymbol{\varepsilon}_{t+1}^F \sim \phi_t^F(\cdot|\mathbf{u}^{pF}) \;\; t\text{=}0,1,\dots,h\text{-}1 \tag{3.3g}$$

$$\mathbf{w}_0^{h-1,F} \textit{ given scenario} \quad (3.3h)$$

$$\mathbf{x}_0^F \textit{ given} \quad (3.3i)$$

$$p^F \triangleq \{m_t^F(\cdot); t = 0, 1, \dots, h-1\} \quad (3.3j)$$

$$\textit{any other constraints t=0,1,...,h-1} \quad (3.3k)$$

At the beginning of each year, each farmer, which is assumed to behave as a rational and selfish agent in a MAS, recursively solves the above problem and selects the land allocation to each crop typology that maximizes its objective function J^F at the end of the growing season. The optimization algorithm used in this work is simulation-based, namely each farmer evaluates each feasible planning action and selects the optimal one according to its objective. The problem time horizon h is thus equal to one year. As shown in Figure 3.1, this optimization process must be repeated until the convergence with the water supply is reached. Once the iterative process stops, the planning decisions cannot be modified until the next year and only the optimal management actions can be implemented until then.
The correspondence between the variables included in Problem 3.3 and the theoretical concepts described in Chapter 2 is highlighted in the following.

1. **Farmers' Design objective** J^F (eqs. 3.3a and 3.3d): maximize the expected income deriving from end-of-year sales of crop products, namely

$$J^F(\mathbf{u}^{pF}) = E_{\{\varepsilon_t\}_{t=1,\dots,h}}[\sum_i^{n_f} Y_{real}^i(\mathbf{x}_0^{h,F}, \mathbf{u}^{pF}, \mathbf{u}_0^{h-1,F}, \mathbf{w}_0^{h-1,F}, \boldsymbol{\varepsilon}_1^{h,F}) \cdot price^i(\mathbf{u}^{pF})] \quad (3.4)$$

where n_f is the number of fields owned by the farmer, Y_{real}^i $[\frac{kg_{market}}{cell}]$ the crop yield obtained in field $i$namely the marketable fraction of the harvested biomass, simulated through the Crop Growth Model (Section 3.2.1), and $price^i(\mathbf{u}^{pF})$ is the price of the crop planted in the field i and the product between yield and price consists in the step-cost $g^F(\cdot)$ in eq. (3.3d).

2. **Planning actions** $\mathbf{u}^{pF}$ (eq. 3.3c) belong to the following feasibility set $\mathcal{U}^{pF}$

   - *Crop choices*
     - Single/Multi-year crop

  - Legume/conventional (for food)/conventional (for energy)/energy/industrial crops
  - C_3/C_4 crops
  - Genetically-improved plants
- *Irrigation technique*
  - Irrigation technology
  - Moisture estimation methods through sensor technologies
- *BMPs*
  - Crop rotation
- *Others*
  - Land allocation
  - Multiple/Inter/Relay cropping

3. **Management actions** $\mathbf{u}_t^F$ (eq. 3.3f) belong to the following feasibility set $M_t^F(\cdot)$

   - *Irrigation Management*
     - Full/Deficit irrigation
     - Irrigation frequency and amount
   - *Use of fertilizers and pesticides*
   - *BMPs*
     - Conservation tillage
     - Manure management
     - Mulching

4. **State variables** $\mathbf{x}_t^F$ (eq. 3.3e) are modeled though a Crop Growth Model (see Section 3.2.1)

   - *Soil water content*
   - *Soil nutrients content*
   - *Crop growth stage*

5. **Stochastic and deterministic disturbances** $\boldsymbol{\varepsilon}_{t+1}^{F}$ (eq. 3.3g), $\mathbf{w}_0^{h-1,F}$ (eq. 3.3h) include the hydro-climatic and socio-economic scenarios previously introduced

- *Temperature distribution during the year*
- *Rainfall events distribution and intensity during the year*
- *Water supply from upstream reservoirs*
- *Crops' market prices at the end of the year*
- *Cost of new equipments or appliances*
- *Cost of consumables (fertilizers, pesticides,...)*
- *Electricity and bio-fuel prices at the end of the year*

The attempt of describing through a numerical model the whole farmers' decision-making process accounting for every possible alternative available to farmers in real world conditions goes beyond the possibilities and space of this thesis. Thus, with reference to the above list, the following simplifications were made.

1. **Farmers' Design objective**, namely the *expected income* at the end of the year, could be upgraded to the *expected profit* if further information concerning costs deriving crop production activities were available.
2. **Planning actions**
   - *Crop choices*
     - Multi-year crops were not considered in the numerical analysis because farmers' planning should be modeled over a longer time horizon than one year. In addition, this choice involves, as previously highlighted, a significant risk of capital loss, and thus a more advanced model of farmers' risk-aversion would be necessary to provide interesting results.
     - The distinction between C_3, C_4 and genetically-improved cultivars was not taken into account: in fact, accounting for all the existing cultivars of each crop would generate a too high number of alternatives. Thus, representative crop growth and productivity data were used for each crop typology without delving into the details of each particular crop species.

- The feasibility set $\mathcal{U}^{pF}$ is therefore restricted to 6 possible crop choices: sugar beet, tomato, permanent grass, maize, soybean and rice were considered, being them the most common crops in the Italian agricultural systems.

- *Irrigation technique*
  - Despite the existence of many different irrigation technologies, only surface and sprinkler irrigation were considered in this work, being the most common in Italy. Anyway, it is straightforward to extend the analysis to other technologies.
  - Moisture estimation methods through sensor technologies were not instead considered, because they are currently used only in very dry areas, whereas in Italy irrigation timing is generally fixed by pre-established rotational irrigation schedules.
- *BMPs*
  - Crop rotation practices were not considered because, as Section 3.2.1 shows, no nutrients balance and pests diffusion dynamics was included in the crop growth model.
- *Others*
  - Multiple/Inter/Relay cropping methods were disregarded not only because of their infrequent application, but also because of the lack of information existing in literature concerning quantitative effects of crops concurrent development on final crop yields.

3. **Management actions** were not accounted for. *Irrigation Management* practices are difficult to apply in rotational irrigation systems. The *Use of fertilizers and pesticides* and the implementation of *BMPs* could be modeled only with more advanced crop growth and soil balance models (e.g. SWAT).

4. **State variables**:

   - *Soil water content* and *Crop growth stage* are the basic state variables of the Crop Growth Model (see Section 3.2.1, specifically eqs. (3.12) and (3.13) for the former state variable, eq. (3.24) for the latter).
   - *Soil nutrients content* was not included in the analysis because it would require a much more complex model, including the nutrients balance in

the soil, accounting for transport (e.g. due to runoff) and transformation (e.g. mineralization/demineralization) processes.

5. **Disturbances**: *Temperature distribution during the year* and *Rainfall events distribution and intensity during the year* were considered deterministic disturbances, since no statistics (probability distributions) were available about them. Also perfect knowledge of future prices was assumed: other elements of the socio-economic scenario were disregared.

The above simplifications strongly modify the structure of FDMP: Problem 3.3, which includes the optimal control problem to design farmers' management actions, becomes a simple *recursive planning problem*, which will not be formalized because its derivation from Problem 3.3 is absolutely straightforward. The addition of management options will be one of the main future developments of this work.

3.2.1 Crop Growth Model formulation

As visible in eq. (3.4), farmers' design objective J^F is given by the product between a given crop price (deterministic scenario) and the crops' marketable biomass produced during the year. In order to evaluate this latter, a Crop Growth Model is required to simulate the dynamics of the state variables, namely soil water content and crop growth stage.
It is useful to remember that the simulation-based optimization of farmers' choices must be iterated until convergence with the water supply is reached: in the mathematical formulation of the Coupled Model the water supply (input from the WS-MOP) and demand (output) will be highlighted with the superscript ^{*k} to indicate that their current value is the optimal one at the k-ith iteration.

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 of $250x250$ 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 considered[1] during the whole time horizon (a year). The model allows to estimate the expected crop yields at the end of the growing season for each crop typology in each cell. By multiplying yields and crop sale prices it is possible to estimate the corresponding revenue. Finally, the aggregation of the revenues deriving from each crop choice in each cell (i.e. field) belonging to each irrigation unit allows to identify the most profitable crop for each irrigation unit (agent) of the irrigation district (MAS), as eq. (3.4) shows. Given the optimal choice, the district-level water demand can be estimated by aggregating the water demand of each farmer (see eq. 3.19).

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). 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).

$$1 - \frac{Y^i_{real}}{Y^i_{max}} = k_y(1 - \frac{ET^i_{real,tot}}{ET^i_{0,tot}}) \tag{3.5}$$

where Y^i_{max} and Y^i_{real} $[\frac{kg_{market}}{cell}]$ are the maximum and actual yields of the crop planted on cell i, $(1 - \frac{Y^i_{real}}{Y^i_{max}})$ [-] the yield decline caused by the water stress $(1 - \frac{ET^i_{real,tot}}{ET^i_{0,tot}})$ [-], $ET^i_{0,tot}$ and $ET^i_{real,tot}$ [mm] the maximum and actual evapotranspiration during the whole growth period and k_y the crop-dependent proportionality factor between relative yield decline and relative reduction in evapotranspiration. As Figure 3.2 shows, crops that are more sensitive to water stresses have higher k_y values (generally

[1]The 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 therefore it is possible to refer to Section 3.2.2 for the complete list of crop-dependent parameters.

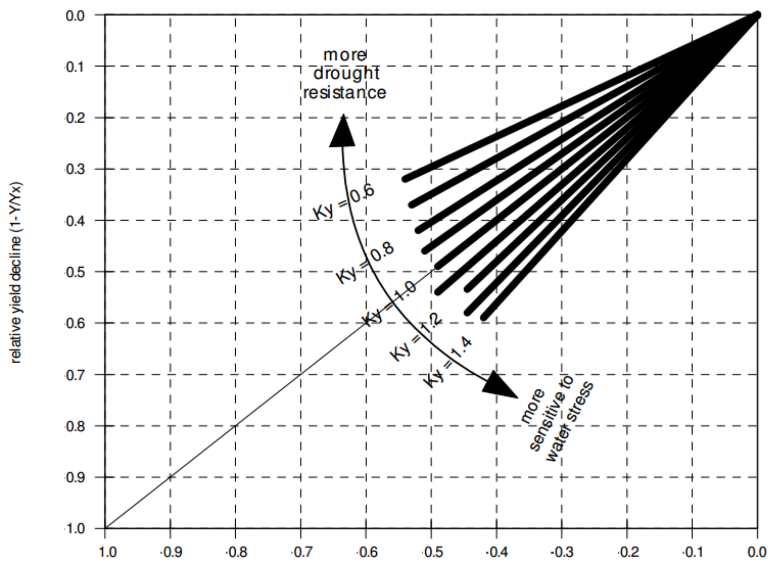

Figure 3.2: Relationship between crops' sensitiveness to water stress and relative yield response factor Ky.

slightly higher than 1), whereas more resistant ones have lower k_y values.
By rearranging eq. (3.5) to the following form

$$Y^i_{real} = Y^i_{max}[1 - k_y(1 - \frac{ET^i_{real,tot}}{ET^i_{0,tot}})] \tag{3.6}$$

it is possible to see that the actual crop yield Y^i_{real} in cell i depends on three terms: maximum achievable yield Y^i_{max} when no water stresses ever happen during the growing season; sum of the daily reference evapotranspiration $ET^i_{0,tot}$ and sum of the daily actual evapotranspiration $ET^i_{real,tot}$ during the whole growth period, defined as follows

$$ET^i_{0,tot} = \sum_{t=1}^{h} ET^i_{0,t} \tag{3.7}$$

$$ET^i_{real,tot} = \sum_{t=1}^{h} ET^i_{real,t} \tag{3.8}$$

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

$$Y^i_{max} = HI_{opt} \cdot B^i_{max} \tag{3.9}$$

where $HI_{opt} \in [0,1]$ is the crop's optimal Harvest Index, an adimensional crop-dependent coefficient representing the marketable fraction of B^i_{max} $[\frac{kg_{DryMassAboveGround}}{cell}]$, that is the maximum biomass produced at the end of an optimal growing season, namely when no nutrients stresses take place[2].
B^i_{max} can be computed as follows:

$$B^i_{max} = \sum_{t=1}^{365} WP \cdot \frac{Tr^i_t}{ET^i_{0,t}} \cdot Ks^i_{b,t} \tag{3.10}$$

where WP represents the crop's Water Productivity $[\frac{kg_{DryMassAboveGround}}{day \cdot cell}]$, Tr^i_t and $ET^i_{0,t}$ [mm] represent the transpiration and reference evapotranspiration at time t, $Ks^i_{b,t} \in [0,1]$ is an adimensional stress coefficient and is defined through a logistic curve defined in the interval $[0, GD_{upper}]$, where GD_{upper} [°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:

$$WP = WP_{std} \cdot f_{CO_2} \cdot S^i \tag{3.11a}$$

$$f_{CO_2} = \frac{\frac{conc_{CO_{2,year}}}{conc_{CO_{2,ref}}}}{1 + 0.000138 \cdot (conc_{CO_{2,year}} - conc_{CO_{2,ref}})} \tag{3.11b}$$

$$conc_{CO_{2,year}} = conc_{CO_{2,ref}} + 2\frac{ppm}{year} \cdot (year - 2000) \tag{3.11c}$$

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} $[\frac{kg_{DryMassAboveGround}}{day \cdot m^2}]$ the crop's water productivity value per unit surface standardized for the $conc_{CO_{2,ref}} = 369.41ppm$ measured in the reference year 2000. In Figure 3.3 some average values of water productivity for C_3 and C_4 crops are represented, proving the capacity of the latter typology to grow higher amounts of biomass with the same amount of transpired water.
Equation (3.11b) updates the standardized values to the current average CO_2 concentration ($conc_{CO_{2,year}}$, Raes *et al.*, 2010), which can be estimated through eq. (3.11c).

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[2]Notice that eq. (3.10) accounts for both water and temperature stresses by means of the terms Tr^i_t and $Ks^i_{b,t}$.

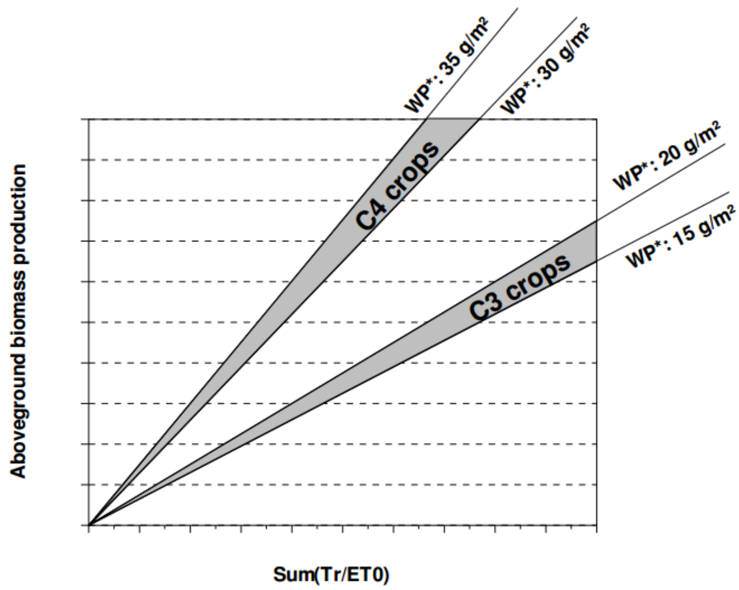

Figure 3.3: Average Water Productivity values of C_3 and C_4 crops: a higher water use efficiency (biomass per unit of transpired, or supplied, water) clearly characterizes the latter crop typology.

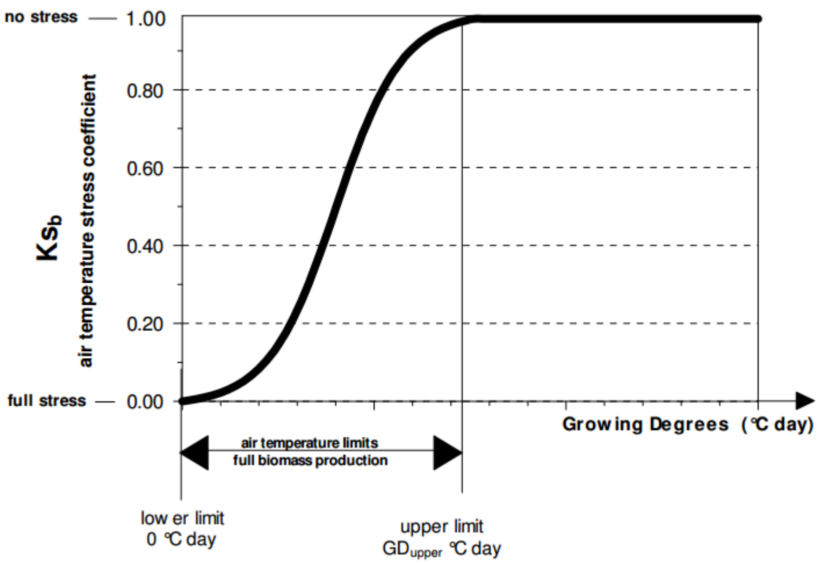

Figure 3.4: Air temperature stress coefficient for reduction of biomass production when average temperature is lower than the optimal one GD_{upper}.

Water balance module

In order to apply the previous equations three last variables for the whole growing season still need to be determined: $ET^i_{0,t}$, Tr^i_t and $ET^i_{real,t}$. 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[3]. 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 operating policy optimization to build the Coupled Model.
In the water balance module (Facchi *et al.*, 2004) each 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. In addition, the soil volume of each cell is divided in 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 $Z^i_{r,t}$. The two layers are modeled as two non-linear reservoirs in cascade (see Figure 3.5). The water percolating out of the bottom layer constitutes the recharge to the groundwater system.
The dynamics of the water content $U^i_{1,t}$ [mm] in the evaporative layer is governed by the following balance equation:

$$U^i_{1,t+1} = U^i_{1,t} + R^i_{t+1} + I^i_{t+1} + Q^i_{r,t+1} + E^i_{t+1} - Q^i_{u,t+1} + Q^i_{i,t+1} \tag{3.12}$$

where all the variables are expressed in [mm] and refer to cell i and time interval $[t, t+1)$. R^i_{t+1} is the rainfall, I^i_{t+1} is the canopy interception, $Q^i_{r,t+1}$ is the net runoff from the cell, E^i_{t+1} is the evaporation, $Q^i_{u,t+1}$ is the water percolating to the transpirative layer and $Q^i_{i,t+1}$ is the irrigation supply.
A similar equation describes the dynamics of the water balance in the transpirative layer:

[3] For the sake of accuracy, the water balance is applied on a hourly basis: hourly data are then aggregated to provide daily ones.

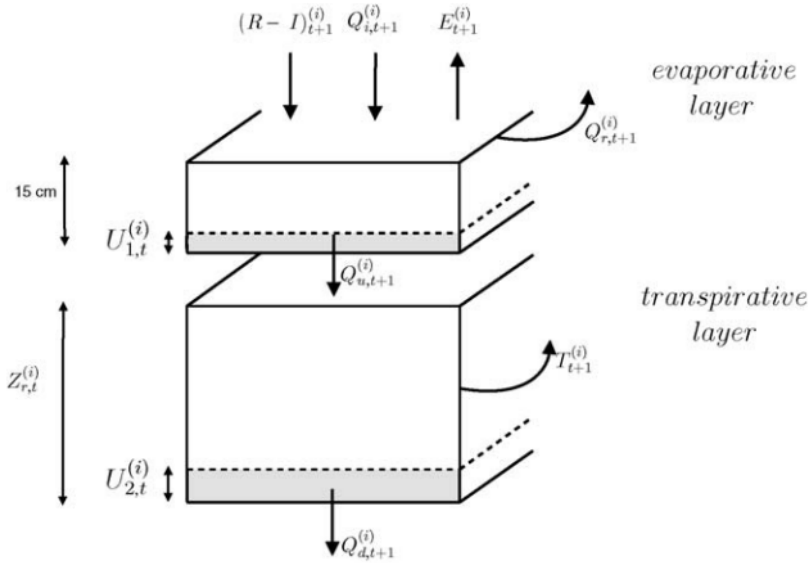

Figure 3.5: Schematic representation of the soil layered structure considered in the distributed model and the corresponding terms involved in the water balance.

$$U^i_{2,t+1} = U^i_{2,t} + Q^i_{u,t+1} - Tr^i_{t+1} - Q^i_{d,t+1} \tag{3.13}$$

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

The evaporation E^i_{t+1} and the transpiration Tr^i_{t+1} in eqs. 3.12 and 3.13 respectively, are computed using the method proposed by Allen *et al.* (1998). The evaporation E^i_{t+1} is determined by multiplying the reference crop evapotranspiration $ET^i_{0,t+1}$ [mm] (computed with the FAO-Penman-Monteith equation) by the evaporative coefficient $K^i_{e,t}$, which depends on $U^i_{1,t}$. The transpiration Tr^i_{t+1} instead is obtained by multiplying $ET^i_{0,t+1}$ by two coefficients: the first is the water stress coefficient $K^i_{s,t}$, which depends on $U^i_{2,t}$; the second is the basal coefficient K^i_{cb}, which strongly depends on the crop growth stage. It follows that

$$Tr^i_{t+1} = K^i_{s,t}(U^i_{2,t}) \cdot K^i_{cb} \cdot ET^i_{0,t+1} = K^i_{s,t}(U^i_{2,t}) \cdot Tr^i_{pot,t+1} \tag{3.14}$$

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

$$Q^i_{t+1} = Q^i_{max,t+1} \cdot a \cdot e^{-d} \tag{3.15}$$

where $Q^i_{j,max,t+1}$ 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 $Q^i_{r,t+1}$ is assumed to be null because the fields are assumed to have drainage canals. In the case this assumption does not hold true for some case studies, the SCS-Curve Number Method (USDA-SCS, 1972, 1986) should be implemented. 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 irrigation district's water demand

The water balance just described allows the evaluation of the hydrologic balance in the root zone. Once water is delivered to a unit, distribution within the unit to each cell takes place firstly on a demand basis and secondly on a rotation basis: at first, priority is given to the cells where water deficits are taking place; then, the remaining water (if any) is distributed among other cells according to a rotation principle.

- Water deficit is defined as follows:

$$D^i_{2,t} = U^i_{2,fc} - U^i_{2,t} \tag{3.16}$$

  where $U^i_{2,fc}$ [mm] is the soil field capacity and $U^i_{2,t}$ [mm] is the soil water content in cell i. Each cell is assumed to be in deficit condition if

$$D^i_{2,t} > \alpha \cdot RAW^i_t \tag{3.17}$$

  where $\alpha \in [0, 1)$[4] and RAW^i_t [mm] is the soil Readily Available Water to the crop (Allen *et al.*, 1998).

[4]Reasonable 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).

Equation (3.17) allows to identify the cells that are experiencing water deficit conditions at each time step t. Assuming to deliver a fixed amount $Q^i_{i,t+1}$ equal to 180 $\frac{mm}{day}$ to restore the optimal water content in each cell in deficit conditions[5], the daily water demand of each irrigation unit (W^{unit}_{t+1}) and of the whole irrigation district (W_{t+1}) can be determined as follows:

$$W^{unit}_{t+1} = \sum_{i=1}^{N^{unit}_{def}} \frac{Q^i_{i,t+1}}{\eta} \tag{3.18}$$

$$W_{t+1} = \sum_{unit=1}^{N_{units}} W^{unit}_{t+1} \tag{3.19}$$

where N^{unit}_{def} is the total number of cells of an irrigation unit, $Q^i_{i,t+1}$ [mm] is positive only if the i-th cell is in deficit conditions, η is the irrigation delivery efficiency (equal to 0.65 for sprinkler irrigation and 0.4 for surface irrigation), N_{units} the number of irrigation units in the irrigation district and W_{t+1} the water demand of the overall irrigation district.

- The actual amount of water distributed within an irrigation unit may be higher or lower than its water demand: in the former case, cells which are not experiencing water deficit conditions will be irrigated; in the latter case, some cells in deficit conditions will not be irrigated[6]. In fact, in order cell i to be irrigated, the water volume $V^{unit}_{distr,t+1}$ already distributed in the irrigation unit at time t must be lower than the maximum volume $V^{unit}_{max,t+1}$ available for irrigation for that day:

$$V^{unit}_{distr,t+1} = \sum_{j=1}^{i-1} (Q^j_{i,t+1} \cdot 10^{-3} \cdot S^j) <= V^{unit}_{max,t+1} \tag{3.20}$$

$$V^{unit}_{max,t+1} = \vartheta^{unit} \cdot Q^S_{t+1} \cdot 86400 \tag{3.21}$$

where S^i [m^2] is the area of cell i, $Q_{i,t+1}$ is equal to 180 $\frac{mm}{day}$ in the irrigated cells (0 otherwise), Q^S_{t+1} [$\frac{m^3}{s}$] is the canal flow rate, i.e. the total water supply

[5] This amount is the quantity averagely used for the border method and therefore rotational irrigation systems are generally managed considering a fixed water height to supply to each cell, regardless of the specific deficit condition of each cell. Another possibility might be to evaluate the amount of water that needs to be supplied to restore the soil water content of the cell to a desired value, e.g. the field capacity (Gandolfi, 2011).

[6] In this case, the priority among cells in deficit conditions will be determined by the rotation principle.

of the whole irrigation district and ϑ^{unit} represents the fraction of the total water supply that each irrigation unit is allowed to withdraw. The total water supply of the whole irrigation district is defined as follows:

$$Q^S_{t+1} = \min[(r^{*k}_{t+1} - q^{MEF}_t)^+, \min(W_{t+1}, q^{max}_t)] \tag{3.22}$$

where r^{*k}_{t+1} is the optimal operating policy (designed on the basis of the water demand W^{*k-1}_t), q^{MEF}_t represents the Minimum Environmental Flow that must be left downstream of the diversion dam (WFD, 2000), q^{max}_t is the maximum flow that can be diverted in the diversion canal, i.e. the minimum between the canal capacity and the licensed flow to be diverted, and W_{t+1} is the current district-level water demand (see eq. (3.19));

Growing Degrees theory

In the previous equations, the values assumed by three fundamental variables – $Z^i_{r,t}$, $K^i_{cb,t}$ and LAI^i_t – 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 determined, see eq. (3.6).
Thus, in order to evaluate $Z^i_{r,t}$, $K^i_{cb,t}$ and LAI^i_t, a model of the daily crop growth was implemented. The model is based on the concept of Growing Degrees (GD, 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

$$GD^i_t = \begin{cases} 0 & \text{if } T^i_{av,t} < T_{base} \\ T^i_{av,t} - T_{base} & \text{if } T_{base} < T^i_{av,t} < T_{cutoff} \\ T_{cutoff} - T_{base} & \text{if } T^i_{av,t} > T_{cutoff} \end{cases} \tag{3.23}$$

where $T^i_{av,t}$ is the average temperature at day t on cell i and T^i_{base} and T^i_{cutoff} [°C] are respectively the base and cutoff temperature of the crop planted on cell i. The

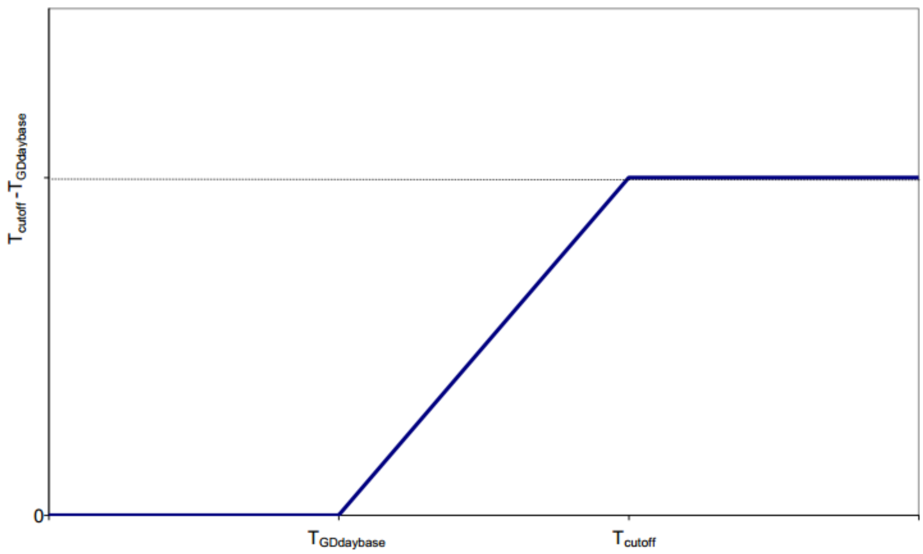

Figure 3.6: graphilcal representation of the relationship between daily average temperature and accumulated growing degrees (eq. 3.23).

shape of the function above is shown in Figure 3.6.

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:

$$accGD_{t+1}^i = accGD_t^i + GD_{t+1}^i \tag{3.24}$$

In accordance with this theory, the database of the software IDRAGRA (Gandolfi, 2011) provides the piece-wise linear functions relating the accumulated growing degrees $accGD_t^i$ to the values of crop parameters $Z_{r,t}^i$, $K_{cb,t}^i$ and LAI_t^i[7]. Specifically, as the maize-related example in Figure 3.7 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 interpola-

[7]For 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 eq. (3.24), which in fact can be seen as a function $T = f(t)$.

tion. 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 3.8 referring to the K_{cb} parameter.

Sowing date

Anyway, in order to apply eq. (3.24), 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 t of the year in which the two following conditions are satisfied

$$\begin{cases} t \geq SowingDate_{min} \\ \frac{\sum_{j=t-4}^{t} T_{av,j}^{i}}{5} \geq T_{req} \end{cases} \tag{3.25}$$

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).

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 eq. (3.6) 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 3.7, this threshold is 1340). In conclusion, harvesting is carried out in the first day satisfying the following condition:

$$t : accGD_t^i \geq PHU \tag{3.26}$$

where $accGD_t^i$ is computed through eq (3.24).

```
mais classe 300
175 # SowingDate_min: minima data di semina(1-366)
10 # Treq: temperatura richiesta per la semina [°C]
8 # Tdaybase: temperatura minima richiesta per lo sviluppo colturale [°C]
30 # Tcutoff: temperatura massima richiesta per lo sviluppo colturale [°C]
false. # V: sensibilità alla vernalizzazione (.true. o .false.)
3 # Tv_min: temperatura minima per una vernalizzazione ottimale [°C]
10 # Tv_max: temperatura massima per una vernalizzazione ottimale [°C]
0 # VFmin: valore minimo del fattore di vernalizzazione [-]
10 # Vstart: giorni di vernalizzazione richiesta affinchè essa inizi
50 # Vend: giorni di vernalizzazione richiesta affinchè essa finisca
7 # A: parametro curva di vernalizzazione
0 # ph_r: risposta al fotoperiodo
8 # daylenght_if: soglia per l'accumulo di tempo fisiologico
20 # daylenght_ins: soglia per l'accumulo di tempo fisiologico
0.5 # p: Parametro colturale ``p"
0.6 # a: Parametro colturale ``a"
2 # cl_CN: Classe CN
1 # uso_irriguo
6 5 5 5 # Numero di punti curve Kcb, LAI, Hc, Sr
# GDD Kcb
116         0
130         0.15
260         0.15
1030        1.107
1240        1.107
1340        0.5
# GDD Lai
116         0
260         0.5
1030        4.5
1240        3.5
1340        3.5
# GDD Hc
116         0
130         0.1
260         0.1
1030        2
1340        2
# GDD Sr
116         0
130         0.5
260         0.5
1030        1.0
1340        1.0
```

Figure 3.7: Example of file containing crop growth data included in the software IDRAGRA, where S_r corresponds to the root depth Z_r.

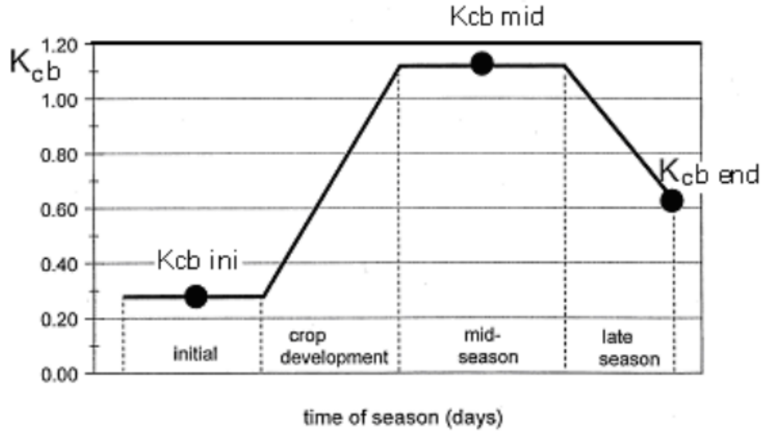

Figure 3.8: Graphical representation of the typical evolution in time of the crop parameter $K^i_{cb,t}$ (similar shapes characterize $Z^i_{r,t}$ and LAI^i_t). It is useful to note the correspondence between Growing Degrees and time (eq. (3.24)), which allows to use the data provided by the database of IDRAGRA.

3.2.2 FDMP inputs and outputs

The aim of this Section is to clarify the correspondence existing between the variables included in the Crop Growth Model described above and the scheme in Figure 3.1. The additional inputs required to run the Crop Growth Model will be therefore listed.

FDMP inputs

As previously discussed, FDMP is influenced by two main exogenous scenarios.

- As concerns the **hydro-climatic scenario**, two options were considered: current and forecasted (in period 2071-2100) climatic conditions. The meteorological inputs required to run the Crop Growth Model in the current climatic conditions are the time series of the average daily rainfall, maximum and minimum temperature, wind speed, maximum and minimum relative humidity and solar radiation. The same time series represent a fundamental input to apply the downscaling procedure and thus build the forecasted climatic scenario, as explained in Section 3.4. It is necessary to take into account the spatial variability of the variables within the irrigation district and, therefore, the time series should be measured by different stations distributed within the study area. Spatial interpolation of the daily values in the different stations is carried out inside the model through the *inverse distance weighting method*, accounting for the nearest 3 stations to each cell.

- As concerns, instead, the **socio-economic scenario**, crops' sale price was computed, in this work, by averaging the sale prices of crop products (absolute prices) in Italy for year 2011 published online by EUROSTAT and ISMEA (Istituto di Servizi per il MErcato Agricolo alimentare).

In addition, several other inputs are required to run the Crop Growth Model, even though during its development care was taken to reduce the parametrization of the equations as much as possible to allow an easier use. Anyway, as shown in the list below, many standardized crop-related inputs are already available in the built-in database, thus good results should be achievable even though no site- or case-specific information is available.

- Most of the required **crop growth-related data** are included in the database of the software IDRAGRA for each crop of interest (see Figure 3.7): minimum sowing date $SowingDate_{min}$, required temperature for sowing T_{req}, base temperature T_{base}, cutoff temperature T_{cutoff}, K_{cb}, LAI, Z_r, PHU and others. Other crop data required to apply eq. (3.6) are the yield response factor k_y, the standardized water productivity WP_{std}, the Harvest Index HI and the minimum temperature for full biomass growth GD_{upper}, which were collected from the manual of the software AQUACROP (Raes *et al.*, 2010) and from FAO Irrigation and Drainage Paper 33 (Doorenbos *et al.*, 1979). Anyway, these two studies provide average data gained from field experience in different regions: being these parameters strongly location-dependent, it is possible to use, if available, datasets more calibrated on the study area.

- The required **irrigation-related data** are the time series of the average daily flow diverted by the water sources (computable given the deterministic scenarios of weather conditions and upstream reservoir operating policy), the partitioning of the irrigation district in units, the correspondence between each unit and the cells belonging to each of them and the share of the daily flow diverted which is assigned to each unit.

- The water balance module requires a series of **soil-dependent parameters**, specifically the hydraulic conductivity in saturated conditions k_{sat}, the soil shape factor N, the soil water content at wilting point U_{wp}, field capacity U_{fc} and saturated conditions U_{sat} and the residual water U_r. Best would be to have these parameters for each cell i of the space domain and for both the evaporative and transpirative layer: in the case so distributed parameters are not available it is always possible to use average data, but this would reduce the significance of the model spatialization.

Finally, the last basic input is represented by the water supply r_t^{*k}, which instead represents the output of the WSMOP, as will be shown in Section 3.3.

FDMP outputs

The main output of FDMP is the water demand W_t^{*k} (see eq. (3.19)) required by the optimal crop choice determined by equation (3.3b), namely the one that maximizes farmers' objective function (eq. 3.4).

3.3 Lake operating policy optimization problem

The aim of this Section is to formalize the WSMOP. As shown in Figure 3.1, if the convergence criterion is not satisfied a new iteration starts and the output of FDMP, namely the estimated water demand W_t^{*k-1}, becomes the new input to the WSMOP through a feedback loop. On the basis of it, the WSMOP can be solved by means of the SDP algorithm, introduced in Section 3.3.2.

3.3.1 WSMOP formalization

The final goal of WSMOP is to determine the optimal operating policy r_t^{*k} which, at each time instant $t = 1, \dots, h$ ($h = 365$) and given the current state x_t^S of the system, suggests the optimal control $u_t^S \in m_t^S(x_t^S)$ to be adopted. Operating policies

from the upstream reservoirs are generally optimized at least on the basis of two fundamental objective functions: minimization of floods on the reservoir shores (J^f) and minimization of water deficits in the downstream irrigation district (J^i).
The formalization of the WSMOP is the following (Galelli and Soncini-Sessa, 2010):

$$J^{*S} = \min_{p^S} J^S \tag{3.27a}$$

$$r_t^{*k} = \arg\min_{p^S} J^S \tag{3.27b}$$

subject to

$$\boldsymbol{\varepsilon}_{t+1}^{a,S} \sim \phi_t^{a,s}(\cdot) \tag{3.27c}$$

$$a_{t+1} = f_t^a(\boldsymbol{\varepsilon}_{t+1}^{a,S}) \tag{3.27d}$$

$$x_{t+1}^S = f_t^s(x_t^S, u_t^S, a_{t+1}) \tag{3.27e}$$

$$x_t^S = s_t \tag{3.27f}$$

$$u_t^S = m_t(x_t^S) \in \mathcal{U}_t^S(x_t^S) \tag{3.27g}$$

$$p^S \triangleq \{m_t^S(\cdot); t = 0, 1, \ldots, h-1\} \tag{3.27h}$$

$$r_{t+1} = R_t(x_t^S, u_t^S, a_{t+1}) \tag{3.27i}$$

$$Q_t^S = f_t^q(r_{t+1}, q_t^{MEF}, q_t^{max}, W_t^{*k-1}) \tag{3.27j}$$

$$W_t^{*k-1} \textit{ farmers' demand scenario generated at iteration k-1} \tag{3.27k}$$

$$\mathbf{x}_0^S \textit{ given} \tag{3.27l}$$

where

- in eq. (3.27a) the design objective J^S is defined as follows:

$$J^S = \lambda \cdot J^f + (1-\lambda) \cdot J^i \tag{3.28}$$

  where the *weighting method* through the coefficient λ is applied to transform a Multi Objectives Problem in a Single Objective one[8], although in this work the weight assigned to the floods reduction objective was zero, in order to focus

[8]The 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).

on the irrigation demand problem; thus, by applying the Laplace filtering criterion (Soncini-Sessa *et al.*, 2007) and considering a finite horizon h, the two objectives can be defined as follows

- *Floods reduction objective*

$$J^f = E_{\{\varepsilon_t^{a,S}\}_{t=1,\dots,h}}[\sum_{t=0}^{h-1} g_t^f(x_t^S)] \tag{3.29a}$$

$$g_t^f = \begin{cases} 0 & \text{if } h_t < h_{thr} \\ a \cdot h_t^4 + b \cdot h_t^3 + c \cdot h_t^2 + d \cdot h_t + e & \text{if } h_t \geq h_{thr} \end{cases} \tag{3.29b}$$

  where $h_t = f(x_t^S)$, $g_t^f(x_t^S)$ $[m^2]$ expresses the daily flooded area if the lake level h_t exceeds a threshold level h_{thr} and the parameters $a, \dots, e$ can be estimated using sets of historical measures of lake levels and the corresponding flooded areas;

- *Water deficit minimization objective*

$$J^i = E_{\{\varepsilon_t^{a,S}\}_{t=1,\dots,h}}[\sum_{t=0}^{h-1} g_t^i(Q_{t+1}^S, W_t^{*k-1})] \tag{3.30a}$$

$$g_t^i = [(W_t^{*k-1} - Q_{t+1}^S)^+]^{nF} \tag{3.30b}$$

  where W_t^{*k-1} is farmers' expected water demand at iteration $k-1$, Q_t^S is the daily water availability to the irrigation district (eq. (3.27j)); nF is farmers' risk-aversion factor, which was initialized to 1, but nothing prevents it from being chosen equal to 2, given the strong risk-aversion that typically characterizes farmers' behavior.

- in eq. (3.27d) the reservoir inflow a_{t+1} is the outflow of the upstream catchment and depends on the disturbance $\boldsymbol{\varepsilon}_{t+1}^{a,S}$ which is assumed to be a white noise and is described by a log-normal probability distribution $\phi_t^{a,S}(\cdot)$ (eq. (3.27c)), which can be built by knowing the daily mean and standard deviation of inflows time series;

- eq. (3.27f) shows that the only state variable of the system is the reservoir storage s_t, which can be computed through the following mass balance equation, which defines eq. (3.27e):

$$s_{t+1} = s_t + a_{t+1} - r_{t+1} - S(s_t) \cdot e_{t+1} \tag{3.31}$$

where r_{t+1} is the actual release from the reservoir, e_{t+1} is the evaporated volume per unit of surface area and $S(s_t)$ is the storage-dependent lake surface area: in eq. (3.27e) these terms were disregarded because unimportant in the case of big reservoirs (at the Italian latitudes at least);

- eq. (3.27g) shows the dependence of the and feasibility set $\mathcal{U}_t$ (and thus of the decision u_t) on the current state x_t;
- eq. (3.27h) points out that the p^S is a point-valued operating policy, namely at each time step it can assume a single value[9];
- in eq. (3.27i) the actual release r_{t+1} is governed by a function $R_t(s_t, u_t, a_{t+1})$ portrayed in Figure 3.9, which accounts for any possible deviation of the actual release from the decision u_t^S due to unintentional spills or any other physical or legal constraints;
- eq. (3.27j) can be evaluated through eq. (3.22) by replacing r_{t+1}^{*k} with r_{t+1};
- eq. (3.27k) highlights that the irrigation water demand W_t^{*k-1} is the water demand scenario estimated by the FDMP model through eq. (3.19) at iteration $k-1$;
- finally, eq. (3.27l) defines the initial condition of the state variable of the system, namely the initial storage.

WSMOP inputs

The main inputs are instead the estimated downstream water demand W_t^{*k-1} at the previous iteration (which, just to recall, is equal to the historical water allowance $\hat{W}_t$ at the first iteration) and the probability density function of the observed inflows to the reservoir $\{\varepsilon_t^{a,S}\}_{t=1,\ldots,h}$, represented as a stochastic disturbance. Other inputs are the value of the Minimum Environmental Flow and the water level h_{thr} above which floods start to occur.

[9]Point-valued operating policies have been extensively proved to be less effective than set-valued ones, which suggest a set of possible decisions with the same performance in the long term. In fact, instead of imposing a unique optimal choice, they let Regulators decide among a few possibilities according to their experience and understanding (Soncini-Sessa *et al.*, 2007). However, set-valued policies are beyond the aim of this work and could be the subject of possible future developments.

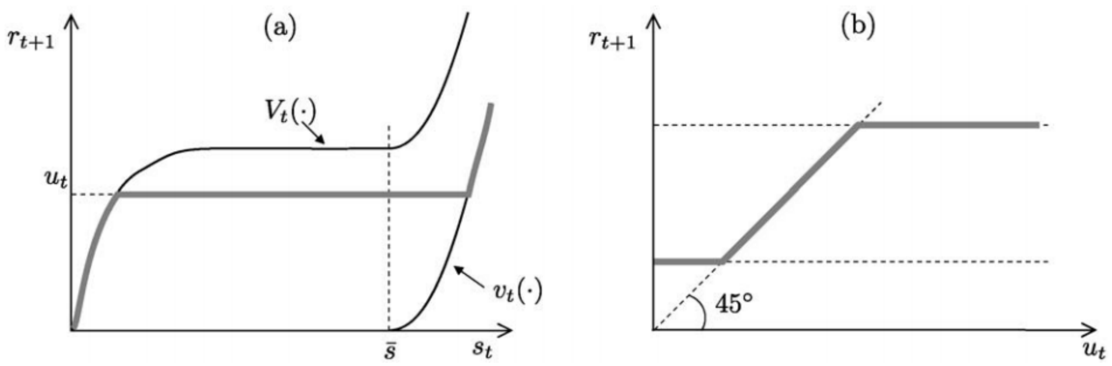

Figure 3.9: The minimum and maximum release functions $v_t(\cdot)$ and $V_t(\cdot)$ and two sections (heavy line) of the release function $R_t(\cdot)$: (a) with respect to the storage s_t, given a_{t+1}, e_{t+1} and u_t; (b) with respect to the release decision u_t, given s_t, a_{t+1} and e_{t+1} (Soncini-Sessa *et al.*, 2007).

WSMOP output

The output of the WSMOP is represented by the optimal operating policy r_t^{*k} defined by eq. (3.27b). The actual water supply of the irrigation district Q_{t+1}^{S*k} can be computed through eq. (3.27j) by replacing r_t with r_t^{*k}. As Figure 3.1 shows, this information is communicated to farmers, which are allowed to re-optimize their choices by solving again FDMP on the basis of the new expected water availability.

3.3.2 Optimal policy computation: Stochastic Dynamic Programming algorithm

The resolution of Problem 3.27 (a Pure Management Problem) requires, as said, the design of the reservoir operating policy r_t^{*k}. Different approaches can be followed to determine an optimal policy.

- The *Functional Approach* determines the optimal policy as a succession of control laws upon which no conditions are imposed. This approach is used to determine either on-line policies or off-line policies through *Stochastic Dynamic Programming* (SDP), with algorithms based on the numerical resolutions of the Bellman equation, as will be better explained in the following (see Yeh (1985) for a review of the first applications of SDP to water resources management and Soncini-Sessa *et al.* (2007) for recent improvements).

- The *Parametric Approach* instead fixes a priori the class of functions to which the control law must belong, so that a particular function, and also a particular policy, is defined by a finite number of parameters and the policy design will consist in identifying the values of the parameters that minimize the objectives (Soncini-Sessa *et al.*, 2007). This approach is generally used to determine off-line policies when the algorithms based on SDP cannot be used because of too high computational requirements (that grow exponentially with the system dimension).

- At last, *Learning Approaches* leave the system to evolve under a suitable algorithm, which experiments with alternative controls until, by trial-and-error, it identifies the optimal policy (Castelletti *et al.*, 2010). The interesting feature of these approaches, based on *Reinforcement Learning* algorithms developed in the Artificial Intelligence field, is that they allow to determine the optimal policy considering, in the system model, also the deterministic inputs $\mathbf{w}_t$.

In this work, the Functional Approach was adopted and, in particular the optimal operating policy of the upstream reservoir was obtained using the Stochastic Dynamic Programming algorithm (SDP, see Bellman, 1957, 1962). The computation of the optimal cost-to-go, namely the expected cost that one would incur in starting from a given state and adopting the optimal decision thereafter can be determined through the the so-called Bellman equation (Bellman, 1957, 1962), defined as follows:

$$H_t^{*S}(\mathbf{x}_t^S) = \min_{\mathbf{u}_t^S \in \mathcal{U}_t^S(\mathbf{x}_t^S)} E_{\boldsymbol{\varepsilon}_{t+1}^S \sim \phi_t(\cdot)}[g_t^S(\mathbf{x}_t^S, \mathbf{u}_t^S, \varepsilon_{t+1}^S) + H_{t+1}^{*S}(x_{t+1}^S)] \tag{3.32}$$

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, and allows to derive the optimal control law $m_t^{*S}(\mathbf{x}_t^S)$ for each state $\mathbf{x}_t$:

$$m_t^{*S}(\mathbf{x}_t^S) = \arg \min_{\mathbf{u}_t^S \in \mathcal{U}_t^S(\mathbf{x}_t^S)} E_{\boldsymbol{\varepsilon}_{t+1}^S \sim \phi_t(\cdot)}[g_t(\mathbf{x}_t^S, \mathbf{u}_t^S, \varepsilon_{t+1}^S) + H_{t+1}^{*S}(\mathbf{x}_{t+1}^S)] \tag{3.33}$$

As the Bellman's Principle of Optimality states, this sequence of decisions could be optimal because each single decision would be optimal for its own stage. Thus, knowing the Bellman function is a sufficient condition for knowing the optimal policy.

3.4 Projected hydro-climatic scenario for climate change impacts assessment

Over the next century, climate change is expected to strongly modify current climatic regimes and affect water availability and balances all over the world. With the aim of minimizing possible negative impacts, each water user should be aware of the changes happening and adapt to them. This holds true particularly for highly water consuming activities, as agricultural ones are, and for Regulators who have to plan the management of reservoirs.

Given the Coupled Model previously described it is possible to assess the magnitude of climate change impacts on water systems management and farmers' activities, as well as the effectiveness of their co-adaptation to the changing climate. By glancing at Figure 3.1 it is quite intuitive that this analysis can be developed by feeding the Coupled Model itself with a hydro-climatic scenario that replaces the time series measured in the meteorologic stations with thos forecasted in the future. Specifically, farmers' planning must adapt to forecasts of the meteorologic variables considered (see Section 3.2.2), whereas the Regulator must update the inflow statistics that are used to design the operating policies through SDP.

The methodology followed to generate forecasted time series of these variables in climate change conditions is based on the application of a cascade of models. At first, the emission scenario was chosen among those developed by the Intergovernmental Panel on Climate Change (IPCC, 2000). These scenarios are baseline (i.e. reference) scenarios, which means that they do not take into account any current or future measures to limit greenhouse gas emissions (e.g., the Kyoto Protocol to the United Nations Framework Convention on Climate Change). In this work the emission scenario A2 was chosen as it represents the worst case scenario since it is expected to provoke the highest global temperature increase (from +2 to +5.4°C) among the scenarios proposed by the IPCC.

The second step of the modeling chain is the selection of a General Circulation Model (GCM, in this work the HadCM[10] was chosen), able to build global climate scenarios on the basis of the greenhouse gases and aerosol concentrations provided by the selected emission scenario. However, the horizontal resolution of GCMs reaches

[10]HadCM3 (abbreviation for Hadley Centre Coupled Model) is a coupled atmosphere-ocean general circulation model (AOGCM) developed at the Hadley Centre in the United Kingdom. It was one of the major models used in the IPCC Third Assessment Report in 2001.

cells of a 200 km side, which are too wide to account for specific climate conditions at the basin scale. Thus, a Regional Climate Model (RCM, in this work the RACMo[11] was chosen) must be also used and allows, given the boundary conditions provided by the GCM, to increase the spatial resolution up to cells of 50 km sides. Being this resolution still too rough to provide representative climatic scenarios at the basin scale and therefore because of the possible existence of biases between RCM outputs and the local climate, one last step is necessary and consists in the downscaling method, known as Quantile Mapping, which allows to correct RCM outputs (Déqué, 2007).

This statistical method is applied to three basic time series which will be named as follows: the *historical climate* represents the time series of meteorologic variables measured in the meteorologic stations located on the basin; the *backcast* and *forecast climate scenario* are instead the time series of simulated meteorologic variables of interest provided by an RCM over the backcast (1961-1990) and forecast (2071-2100) periods respectively (Anghileri *et al.*, 2010). These latter data were obtained from the PRUDENCE project (see http://prudence.dmi.dk/ and Christensen and Christensen, 2007).

The Quantile Mapping procedure consists of plotting a simulated value against an observed one, both corresponding to the same probability: this is equivalent to comparing their cumulative density function. If the model were perfect, the plots should align along the diagonal. If this is not the case, from this comparison a correction function for each quantile of the two probability distributions can be estimated. Thus, by applying this method to the two time series provided by the backcast scenario (simulated values) and observations, it is possible to determine a quantile-quantile correction function which, under the fundamental hypothesis that it will not change over the next century, can be applied directly to the two time series of the forecast and backcast scenarios. In mathematical terms:

$$\mathbf{q}_{back}^{sim} = \hat{F}_{corr}(\mathbf{q}^{obs}) \tag{3.34a}$$

$$\hat{\mathbf{q}}_{fore}^{corr} = F_{corr}(\mathbf{q}_{fore}^{sim}) \tag{3.34b}$$

where the unknowns of the two equations are capped, F is the quantile-quantile correction function that is estimated through eq. 3.34a and then applied to eq. 3.34b,

[11]Regional Atmospheric Climate Model, developed by Koninklijk Nederlands Meteorologisch Instituut (KNMI), also known as Royal Netherlands Meteorological Institute.

$\mathbf{q}^{obs}$ is the quantile vector of the observed (measured) time series, $\mathbf{q}^{sim}_{back}$ is the quantile vector of the simulated time series (obtained from PRUDENCE) referring to the backcast period, $\mathbf{q}^{sim}_{fore}$ is the quantile vector of the simulated time series (obtained from PRUDENCE) referring to the forecast period and $\mathbf{q}^{corr}_{fore}$ is the quantile vector of the corrected time series referring to the forecast period.
The final outputs of this procedure are then the corrected (downscaled) meteorologic variables in the forecast scenario: these can be used directly as a new input to FDMP to evaluate possible changes in crop production choices in the future as a consequence of farmers' and Regulator's adaptation to climate change. As concerns the WSMOP (which requires the inflows daily mean and standard deviation) instead, since time series of inflows are clearly not included in climatic models (and thus in the PRUDENCE project), it was necessary to estimate them using a rainfall-runoff model and fed with the downscaled meteorologic variables of the region. Using the estimated inflows time series in the forecast period, operating policies can actually be re-optimized to adapt to climate change: the expected result is an increase of their efficacy and efficiency, as will be discussed by applying this method to the case study.

Chapter 4

Case study: Lake Como system

The Coupled Model formalized in Chapter 3 will be applied to a real world water system to study the mutual influence existing between operating policy design of an upstream reservoir (Lake Como) and farmers' choices in a downstream irrigation district, the Muzza-Bassa Lodigiana district. The study area will be presented in Section 4.1.

The expected result is a reduction of the inefficiencies of the current water supply management by designing a operating policy calibrated on the basis of the expected farmers' choices for the coming year and thus on the basis of their expected actual water demand. In addition, the efficacy of possible mitigation strategies implemented by farmers and Regulator will be assessed by feeding the Coupled Model with a forecasted hydro-climatic scenario, generated by means of the procedure described in Section 3.4.

The results accomplished in the two different climatic conditions will be presented in Sections 4.2 and 4.3 respectively. Finally, Section 4.4 will show the potential impacts of climate change if no adaptation strategies are developed and put into practice and assess the mitigation effects that adaptation strategies may accomplish.

4.1 Case Study Description and Coupled Model application

Case Study Description

The map of the study area is represented in Figure 4.1, whereas a schematic view of the whole system highlighting the main stakeholders downstream of the regulation dam is given in Figure 4.2. The main components of the water system are described in the following.

The Muzza-Bassa Lodigiana irrigation district

The irrigation district considered is located in the Padana Plain in the North of Italy, south-east of the city of Milan. It covers an area of about 740 km^2 which extends from north of Cassano d'Adda (east of Milan) to the Po river and is limited by rivers Lambro and Adda on the western and eastern sides respectively.
The Muzza irrigation district can be divided into two areas, the Northern and Southern parts, which are delimited by underground geological boundaries.
In the Northern part, which is also the largest one (about 550 km^2), water for irrigation (applied mainly through border or sprinkler methods) is supplied by the *Muzza canal* which originates from a diversion dam on the *Adda river* and represents the main stream of a thick distribution network made of smaller canals (more than 400, with a total length of about 4.000 km) that convey water to each unit of the district. In the Southern part instead, the irrigation demand is met thanks to a drainage network from the Northern part, along with wells and pumping systems withdrawing water directly from the Po river.
The cultivated area covers 85% of the whole district and is currently mainly allocated to cereals (especially maize) and permanent grass. Being maize a much more water demanding crop than permanent grass, the irrigation water demand of the district is mainly concentrated in the dry summer months.

The Adda river

The Adda river serves eight run-of-river hydroelectric power plants, with a total installed capacity of 92 MW, and supplies a dense network of irrigation canals that

supports five irrigation districts (Muzza district included) with a total surface of 1.400 km^2, where the traditional crop typology is very similar to the Muzza one (maize and permanent grass are the most common crops).
Being the Adda river the *Lake Como* effluent, its flow rate and thus the water supply to downstream users depend on the release from the lake, which is regulated through the Olginate dam and, of course, always accounts for a Minimum Environmental Flow that must be always guaranteed to allow ecosystems life, as suggested by the Water Framework Directive (WFD, 2000).

Lake Como: the upstream reservoir and its traditional management principles

The reservoir of the water system is Lake Como, which has a surface area of about 145 km^2 and an active storage of 260 Mm^3. It is fed by a 4500 km^2 catchment, characterized by a typical alpine pluviometric regime that produces an inflow process (averaging 4.73 $\frac{Gm^3}{year}$) which is scarse in winter and summer and shows peaks in late spring and autumn. The two inflow peaks are mirrored in two storage peaks: one in late spring (the highest in the whole year, because snow melt intervenes) and one in autumn.
In order to optimize releases according to downstream irrigation water demands – which are mainly concentrated in summer months – and hydroelectric demands – which instead vary with the Italian electricity demand during the year – regulation is necessary and thus, in 1946, a regulation dam was built at the lake outlet. The license act of Lake Como states that the *regulation range* of the lake Regulator, namely the interval referred the lake level in which he can freely choose the release, is between 0.50 and 1.30 m at the Malgrate hydrometric station; the dam gates must be completely opened when the level exceeds 1.30 m and release must not exceed the inflow when the level equals 0.50 m. If the lake level exceeds 1.30 m in fact, floods start to occur: the most sensitive area is the city of Como, which is located at the lowest elevation. If, on the contrary, the lake level is below 0.50 m risks for future water availability may rise and some recreational and tourism related activities may be negatively affected.

Given these general management rules, the Regulator followed so far some additional regulation principles to handle the conflict between interests of irrigation districts and hydropower companies. During the irrigation season (say from April to September), being the total water demand of the irrigation districts located downstream of

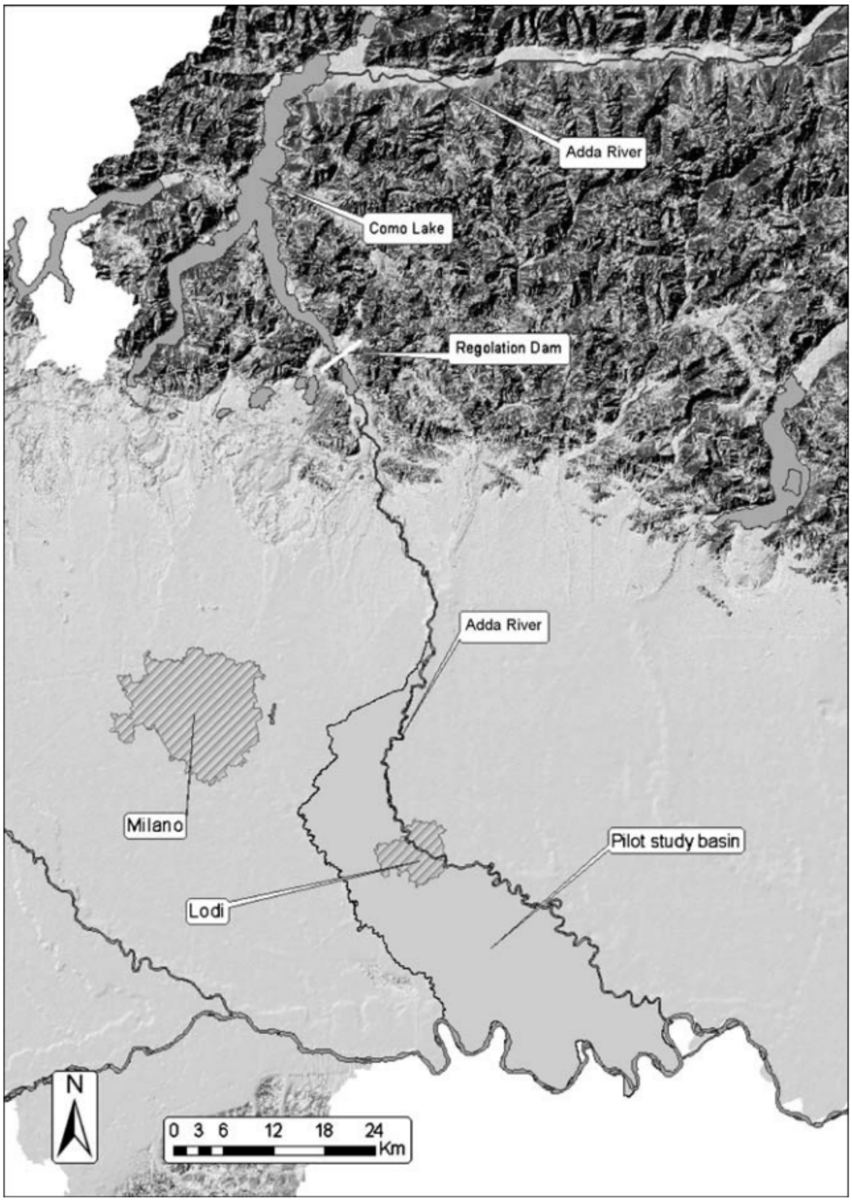

Figure 4.1: Geographical localization of the study area (Galelli *et al.*, 2010)

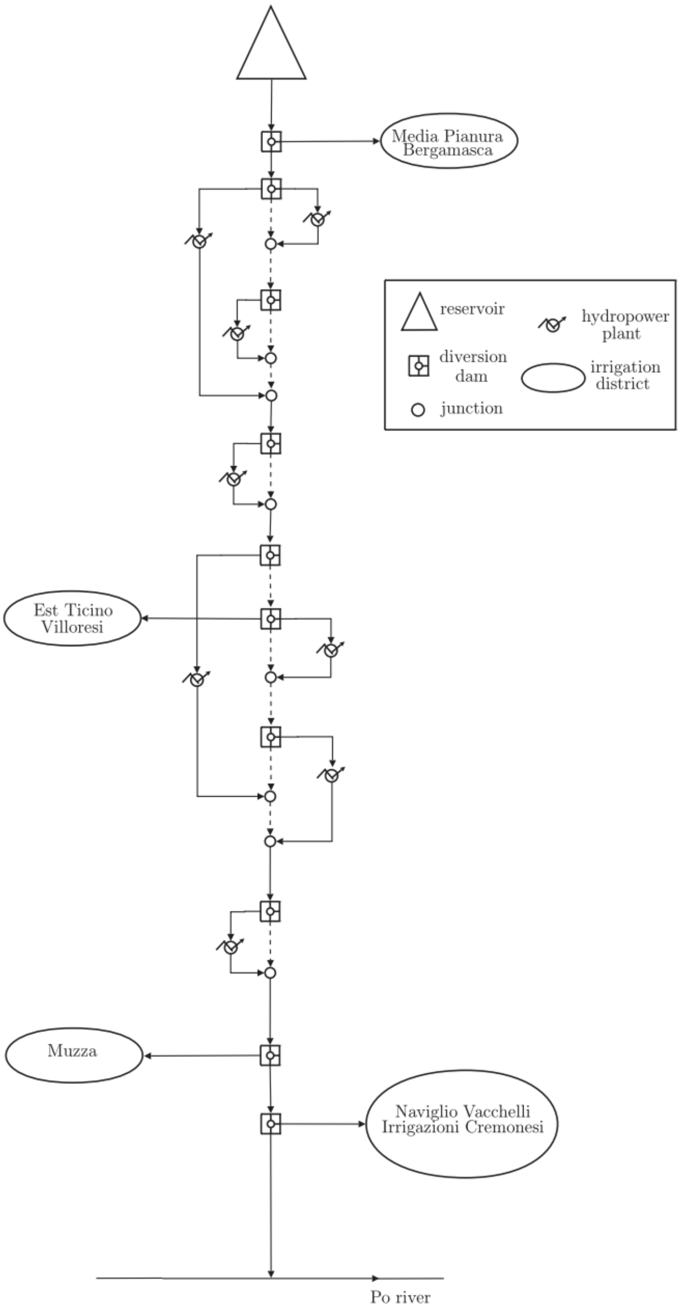

Figure 4.2: Scheme of the water system which the Muzza irrigation district belongs to (Galelli *et al.*, 2010): the triangle on top represents Lake Como.

all the power plants larger than the hydropower water demand, the Regulator aims at satisfying the first so that the second is satisfied at the same time. In this way the competition between farmers and hydropower companies during the irrigation season is at least reduced, even though not completely removed because the optimal alternative for hydropower companies would be a release matching perfectly their demand during the summer months (that is lower than the irrigation one) to store more water to release during winter (when there the energy demand is higher and in general electricity prices are higher): it is quite evident then, that during these months the conflict is solved in favor of irrigation districts. During winter instead, the conflicting interests for the autumn storage has for a long time been solved by a *gentlemen's agreement* according to which the regulation is in favor of hydropower plants (Galelli *et al.*, 2010).

From the considerations above, it emerges that the operating policy has always been accounting for two main objectives: *floods reduction* on the Lake Como shores and *downstream water supply*. These are exactly the two design objectives that will be considered in the operating policy design introduced in Section 3.3.

Anyway, up to now, the general regulation principles above are applied considering a given reference trajectory of the demand, the current *water allowance*. While the hydroelectric demand can be considered a *cyclostationary* signal as a simplifying assumption (and thus it could be reasonable to use a fixed demand), irrigation demand – in terms of volumes of water required and timing – is strongly affected by farmers' choices and mainly by their choices on the crops to plant in each growing season. In fact, big differences in water demands characterize different crops: for instance, maize is much more water demanding than permanent grass in terms of total annual water volumes, but while the former requires these volumes only in the summer months, the water demand of the latter is more distributed during the year. For this reason, irrigation demand may change strongly year by year.

Therefore, in recent years, a series of significant droughts events in the study area has elicited interest in water savings and enhanced attention to water losses produced when the flow diverted into the Muzza main canal is higher than the irrigation water demand (and the net diverted flow is thus higher than the irrigation supply), as it happens, for instance, during precipitation events.

For these reasons, a operating policy optimization that accounts for the expected demand arising from farmers' expected choices for the coming year is expected to reduce drastically the inefficiencies and water losses of the whole water system.

In order to reach this goal, the Coupled Model was applied to the study area, using site-specific data and considerations that will be detailed in the following.

Application of the Coupled Model

Modeling time step and horizon

The time-step of both the models linked through a loop structure in the Coupled Model is 1 day. This choice is reasonable and realistic because decisions related to both lake regulation and water distribution in rotational irrigation systems are generally taken on a daily basis in real world situations. In addition, considering the Muzza district's size, this time-step is definitely larger than the time required for a released volume to reach the most distant field in the district and thus the regulation does not need to account for the downstream canals dynamics: transport time is thus considered null and no further state variables need to be introduced. The model time horizon h instead is one year: just before the beginning of the new year the Coupled Model is ran to determine the optimal operating policy on the basis of the optimal land allocation to each crop.

Domain size

The spatial domain of the distributed-parameter model coincides with the Muzza-Bassa Lodigiana district (about 740 km^2): considering a regular mesh which divides it into squared cells of 250 m side length, a total number of 11667 cells (N_{cells}) is created. Therefore, since the model employs three state variables U_1, U_2 (water content in evaporative and transpirative layers) and $accGD_{t+1}$ (crop's growth stage) for each cell, the dimension of the model state vector is of the order of $3(10^4)$.

FDMP: site-specific input data

With reference to the list of input data of Section 3.2.2 and given the **standard crop-related inputs** (crop growth parameters and sale prices) in the already built-in database of the Coupled Model, three categories of site-specific data are required.

- Each of the N_{cells} is associated to the nearest 3 agro-meteorological stations out of the 11 dislocated on the Muzza district. The **meteorologic time se-**

ries (average daily rainfall, maximum and minimum temperature, wind speed, maximum and minimum relative humidity and solar radiation) associated to each cell are computed by interpolating the daily (measured or forecasted) data in the 3 stations through the *inverse distance weighting method*. In addition, *sowing and harvesting dates* are determined by applying conditions 3.25 and 3.26 respectively to the meteo data series of each meteorological station: in this way a sowing and harvesting date is found for each of the 11 stations and associated to all the nearest cells (Gandolfi, 2011). Time series of the meteorological variables measured in the agro-meteorological stations were available for the period 1993-2004: they represent the current hydro-climatic scenario but also allow to build the time series of the forecasted hydro-climatic scenario (referring to period 2071-2100) through the dowsncaling procedure (see Section 3.4).

- As concerns **irrigation-related inputs**, each of the N_{cells} is associated to a value describing the irrigation efficiency of the technology that is used there to irrigate and to one of the 66 irrigation units which the Muzza district is divided in: this latter correspondence is fundamental to model the water distribution inside the district, because each unit receives, by regulation, a fixed share of the total flow diverted by the Muzza canal and then each farmer partitions it among its cells according to conditions 3.17 and 3.20. The total flow diverted by the Muzza canal depends on the optimal operating policy r_t^{*k} of Lake Como at the k-ith iteration of the Coupled Model (eq. (3.22)).

- Galelli *et al.* (2010) computed the **soil parameters** deriving them from the combination of the 1:250.000 pedological map of the district, which includes 60 main pedological units, and field observations of the physico-chemical characteristics of the soil profiles representative of each unit. The parameter values were computed by using so-called Pedo-Transfer Functions (PTFs), i.e. empirical relationships that relate the values of the main soil parameters (e.g. water content at field capacity and wilting point, saturated hydraulic conductivity) to the values of selected physico-chemical variables (e.g. bulk density, porosity, organic matter).

WSMOP: site-specific input data

In order to solve the WSMOP described in Section 3.3, a few input data are required.

- In order to apply the SDP algorithm (eqs. (3.32) and (3.33)), the probability density function of the lake inflows ($\varepsilon^S_{t+1} \sim \phi_t(\cdot)$, $t = 1, \ldots, h$) has to be determined. The daily mean values and standard deviations were determined using a 60 years time series (1946-2006) from which the additional observations in each leap year were removed. These parameters allowed to build the daily log-normal probability density function of the inflows. Therefore, the same method was replicated to determine the statistics of the downscaled inflows time series related to period 2071-2100.

- The irrigation demand W^{*k}_{t+1} on the basis of which operating policy is designed through SDP is made of the contributions of five irrigation districts located downstream of the Olginate dam. In order to focus only on the case study area, it was assumed that the irrigation demand of those districts different from the Muzza one is equal to their current water allowance $\hat{W}_{others,t+1}$. Thus, eq. (3.1) is modified as follows:

$$W^{*k}_{t+1} = W^{*k}_{muzza,t+1} + \hat{W}_{others,t+1} \tag{4.1}$$

  where $W^{*k}_{muzza,t+1}$ is computed by means of the Crop Growth Model (eq. 3.19).

Convergence criterion

The Coupled Model was set to stop the iterations between WSMOP and FDMP when the number of cells allocated to different crops between two consecutive iterations is lower than a desired fraction of the total number of cells of the space domain.

Climatic scenarios

The Coupled Model was implemented using two different hydro-climatic scenarios, with the aim of assessing the potential impacts of climate change on WSMOP and FDMP.

Current climatic scenario

The first climatic scenario refers to the current conditions, thus the meteorologic variables used in FDMP and the Lake Como inflows used in the WSMOP are the measured ones in the meteorological stations in the past years (1993-2004).

Forecasted climatic scenario

The second climatic scenario instead refers to the climatic conditions that are forecasted by downscaling the results provided by coupling a global model (GCM) and a regional model (RCM), given the emission scenario A2, which is the worst emission scenario among the ones developed by the IPCC (IPCC, 2000). For this second scenario then, the downscaled meteorologic variables referring to the period 2071-2100 were used as inputs to FDMP and allowed to build the inflows time series, namely the input to the WSMOP, by means of a rainfall-runoff model.

Behavioral scenarios

In addition, for each of the considered climatic scenarios, two possible behavioral patterns of farmers and Regulator were considered, with the aim of assessing the efficacy of the implementation of mitigation strategies.

Lower bound

The first behavioral scenario considers that farmers and Regulator take decisions as they always have in the past. This means that in current climatic conditions, they take decisions independently, thus no information exchange and integration between their decision-making processes takes place: farmers keep on cropping maize and permanent grass and the Regulator optimizes the operating policy on the basis of the current downstream water allowance.
In the forecasted climatic scenario which accounts for climate change, both farmers and Regulator take decisions without realizing the change of climatic conditions and thus still on the basis of their past perception of (referring to the period 1993-2004) of the climatic conditions.

Upper bound

The second behavioral pattern assumes instead an optimal and cooperative behavior of farmers and Regulator: in the first climatic scenario they re-optimize their decisions in an integrated way by exchanging their estimates of their future decisions; in the second climatic scenario they perceive the climatic change happening and thus re-optimize their actions on the basis of the new available information on climatic conditions.

Combinations of the above scenarios

The combination of the above scenarios produces four possible new scenarios, the evaluation of which allows to understand the impacts of different hydro-climatic scenarios given different behavioral responses. Specifically, the final scenarios are:

- Current meteorological conditions
  - Lower bound: current climatic conditions and independent decision making processes, i.e. no information exchange between farmers and Regulator;
  - Upper bound: current climatic conditions and information exchange between farmers and Regulator;
- Forecasted meteorological conditions (climate change)
  - Lower bound: downscaled climatic conditions, no adaptation strategies adopted and independent decision making processes, i.e. no information exchange between farmers and Regulator;
  - Upper bound: downscaled climatic conditions and both adaptation and information exchange between farmers and Regulator taking place.

These scenarios represent an input to the Coupled Model and are used to accomplish different purposes.
First of all, scenarios with the same climatic conditions allow assess the efficacy of the Model itself on *water deficits reductions*, namely the potential beneficial effects

of the information exchange-based interaction between farmers and Regulator to enhance the water supply efficiency.
Secondly, scenarios considering the same behavioral pattern of farmers and Regulator but different climatic conditions allow to estimate the *maximum potential effects of climate change* (since the worst emission scenario was considered) on the system performances and consequent water deficits.
Finally, the results can be analyzed in terms of the variation of farmers' crop choice patterns as a consequence of different climatic conditions to hypothesize *potential changes in crop production activities* that may happen in the next century due to climate change effects.

4.2 Results in current climatic conditions

In current conditions, the efficacy of the Coupled Model in the reduction of water deficits can be figured out by comparing the deficit results given by the upper and lower bound. Just to recall, in the upper bound farmers and Regulator plan their activities and operating policy respectively by interacting and thus mutually adapting their choices. In the lower bound, they behave independently as they always have in the past, namely the Regulator optimizes its operating policy according to the current water allowance and farmers plant mainly maize and permanent grass.

The results show that in the upper bound scenario farmers decide to plant tomatoes in all the cells of the study area instead of maize and permanent grass (crop pattern of the lower bound). This shift is justified by the much higher profitability of the former crop choice pattern with respect to the latter, as well as with respect to any other crop that was considered in this work; in addition, the strong sensitivity of tomatoes to water stresses is mitigated by the re-optimization of the operating policy. Of course this result cannot be but unrealistic: the reason lies in the fact that farmers' income was computed by a simple multiplication between grown biomass and crop price, without considering crop production costs – which are definitely higher for a very sensitive crop as tomatoes than, for instance, maize – and potential shadow prices, e.g. planting tomatoes instead of permanent grass would require farmers to find a supply of animal feedstock for livestock farming activities. In addi-

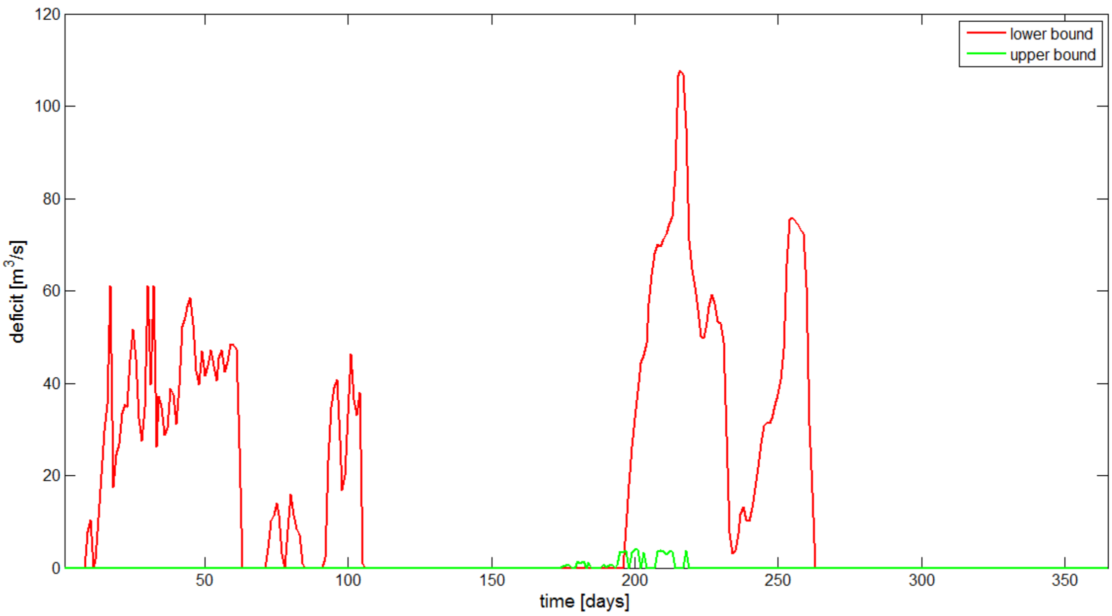

Figure 4.3: Daily water deficit in the lower and upper bound in current climatic conditions: a strong reduction of water deficits is clear if the Coupled Model is implemented.

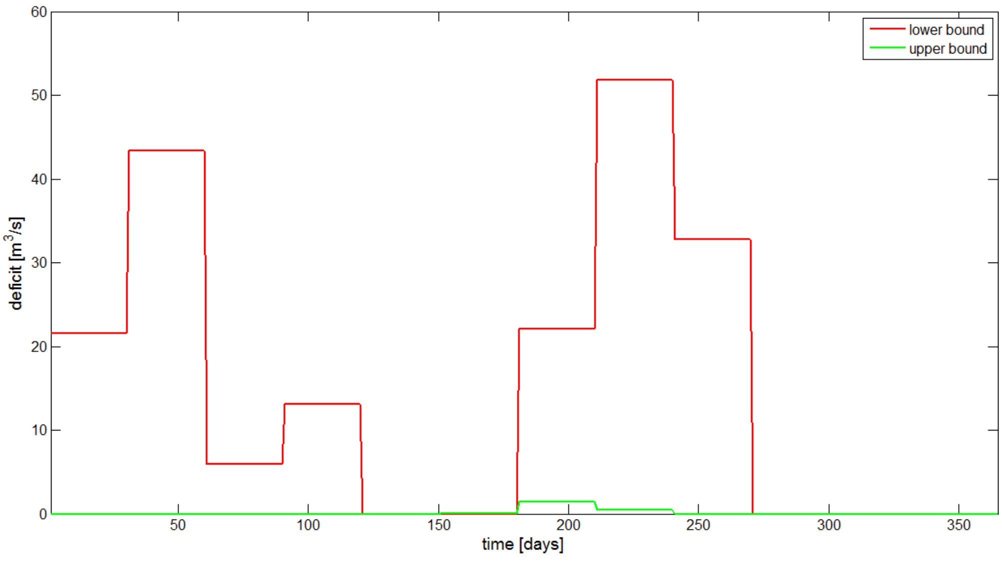

Figure 4.4: Average monthly water deficit in the lower and upper bound in current climatic conditions: a strong reduction of water deficits is clear during the whole year if the Coupled Model is implemented and particularly in the growing season (spring-summer).

tion, the crop price was considered as fixed during the year and independent of the quantity produced: this could be not realistic at all, not only because of the variability of crop prices during the year, but also because if the whole Muzza district were to plant tomatoes and considering that the national consumption of tomatoes is relatively low, their market price would probably decrease, making tomatoes less and less profitable, in favor of other crops. However, as already discussed in Chapter 2 and considering the explorative nature of this work, all these aspects could not be accounted for, but represent a good start for further developments of this work.

Given this due premise on the representativeness of the results of the Coupled Model, the simulation in the upper and lower bounds provides interesting results, which can be compared in terms of water deficits. As visible in Figures 4.3 and 4.4, the water deficit that crops experience during the same year are quite different in the two scenarios. Keeping in mind that water deficits in the upper bound refer to tomatoes and in the lower bound to maize and permanent grass, it is absolutely visible that in the upper bound the water deficits are absolutely reduced with respect to the lower bound.

In the lower bound water deficits are experienced in 145 days a year, whereas in the upper bound only in 26, with a reduction of the number of stress days of about 82%. In addition, in the lower bound water deficits averaged during the whole year are $15.67\frac{m^3}{s}$, while in the upper bound they decrease by almost 99% reaching an average value of $0.16\frac{m^3}{s}$. Figure 4.4 shows the average water deficits on a monthly basis and highlights the good deficit reduction during the main growing season (spring and summer) thanks to the interaction and information exchange between farmers and Regulator. Therefore, even the maximum (peak) water stresses decreases significantly, from $107.70\frac{m^3}{s}$ in the lower bound to $4.02\frac{m^3}{s}$, with a reduction of about 96%.

Figures 4.6 and 4.7 show the convergent evolution of water supply and demand from the lower to the upper bound towards an almost perfect matching. Specifically, in the former representation, some water releases in the early spring are not required by the demand, and thus a significant wastage of water takes place; on the opposite, the latter Figure shows a very high matching between supply and demand, even in the driest summer months. Thus, strong changes in water releases take place between lower and upper bound, since they are tuned on the basis of farmers' esti-

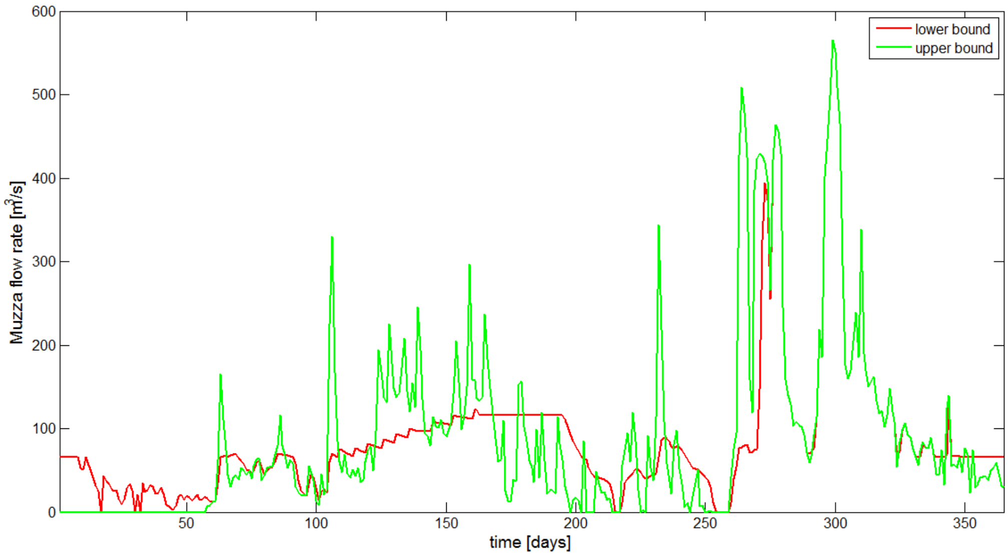

Figure 4.5: Average daily flow rate of the Muzza canal in the lower and upper bound in current climatic conditions: a strong variation is visible to adapt to the water demand deriving from the new optimal farmers' choice, namely cropping tomatoes instead of permanent grass and maize.

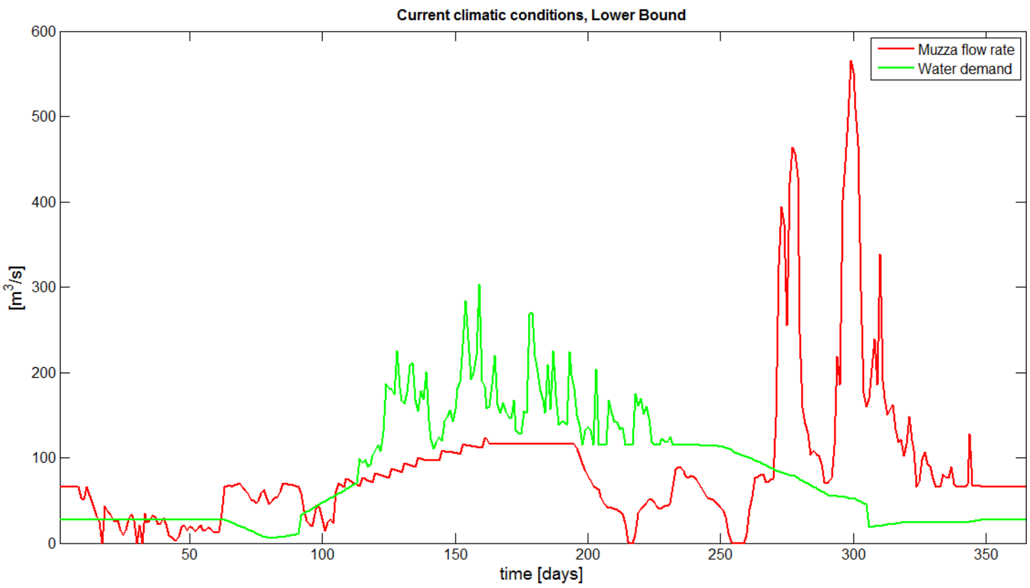

Figure 4.6: Comparison between average daily Muzza flow rate and water demand in the lower bound in current climatic conditions.

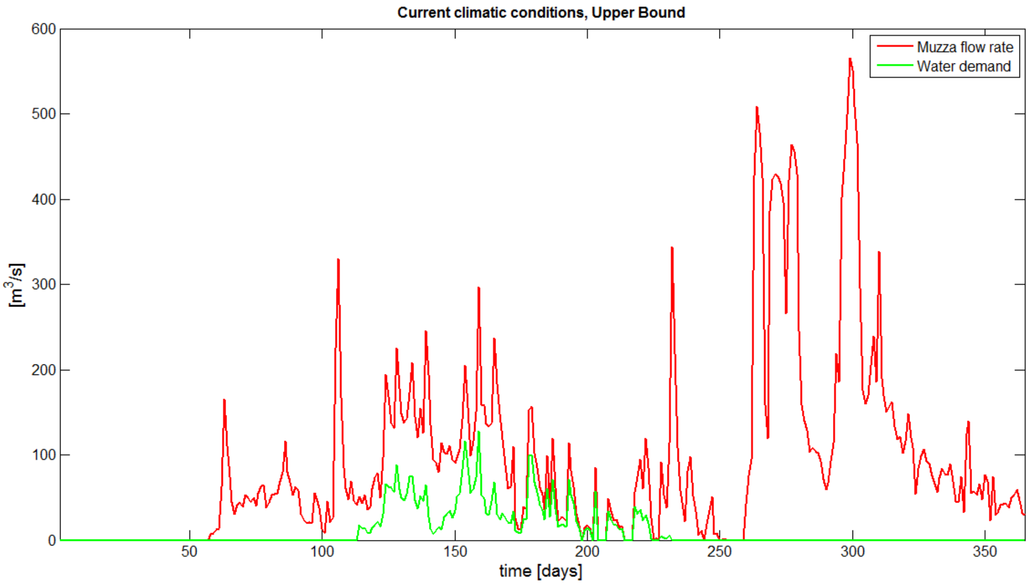

Figure 4.7: Comparison between average daily Muzza flow rate and water demand in the upper bound in current climatic conditions.

mated water demand. Figure 4.5 shows the difference of the water flow in the Muzza canal in the two scenarios.

These results prove very clearly the efficacy of the integration of farmers and Regulator decision-making processes through the information loop on the basis of the Coupled Model to reduce crop water stresses in the current climatic conditions. The beneficial effect of this interaction will be translated into a more efficient water management practice by abating water wastage and, at the same time, an increase in crop production, being plants growth less limited by water availability.

4.3 Results in climate change conditions

By following the same reasoning as in the previous Section, the benefits of farmers' and Regulator's adaptation to climate change are assessed by comparing lower and upper bound scenarios in forecasted climatic conditions.
The results of FDMP show a strong adaptation response by farmers, proven by

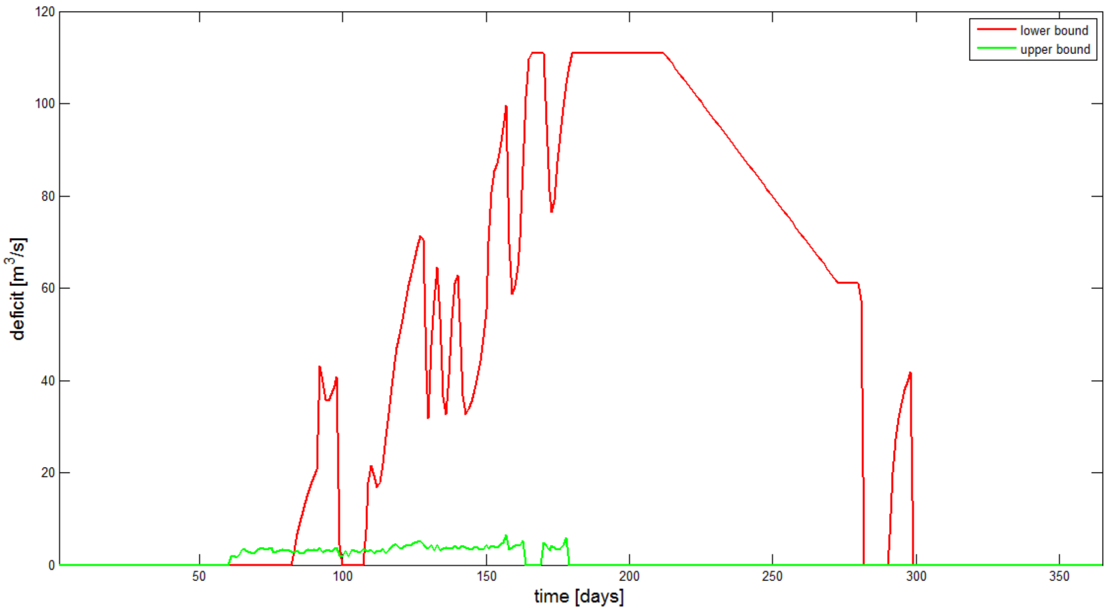

Figure 4.8: Daily water deficit in the lower and upper bound in forecasted climatic conditions: a strong reduction of water deficits is clear if the Coupled Model is implemented.

the almost complete shift of the crop choice pattern from tomatoes to permanent grass: 65 irrigation district over 66 adapt to climate change by modifying their crop choices, only in 1 irrigation district tomatoes are still expected to be more profitable than other crops.

As concerns water availability, in the lower bound water deficits are experienced in 199 days, whereas in the upper bound only in 112 days, with a reduction of the number of stress days around 44%. The average daily water deficits are $39.69\frac{m^3}{s}$, while adaptation simulated with the Coupled Model reduces them to $1.07\frac{m^3}{s}$: a reduction of -97% is accomplished though the application of the methodology developed in this work. Figure 4.9 shows the average water deficits on a monthly basis and highlights the remarkable deficit reductions accomplished during the main growing season (spring and summer) thanks to the adaptation strategies simulated through the Coupled Model. Therefore, even the maximum (peak) water stresses decreases significantly, from $110.89\frac{m^3}{s}$ in the lower bound to $6.60\frac{m^3}{s}$, with a reduction of about 94%.

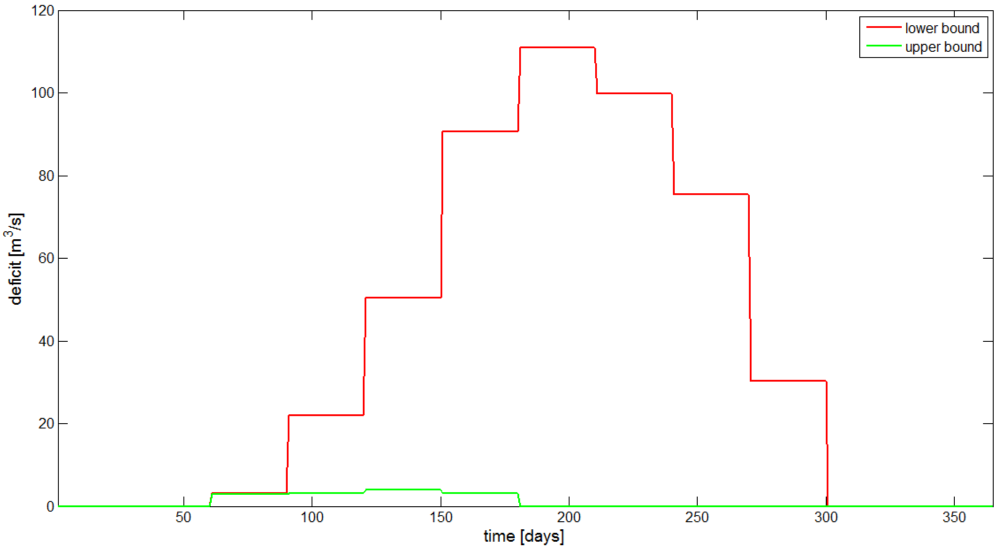

Figure 4.9: Average monthly water deficit in the lower and upper bound in forecasted climatic conditions: a strong reduction of water deficits is clear particularly during the growing season (spring-summer).

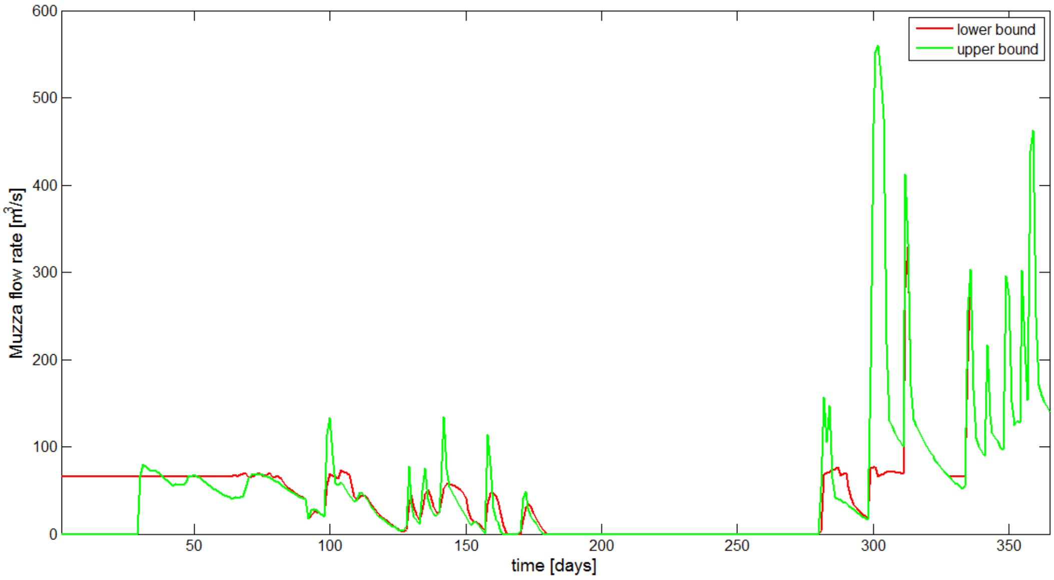

Figure 4.10: Average daily flow rate of the Muzza canal in the lower and upper bound in forecasted climatic conditions.

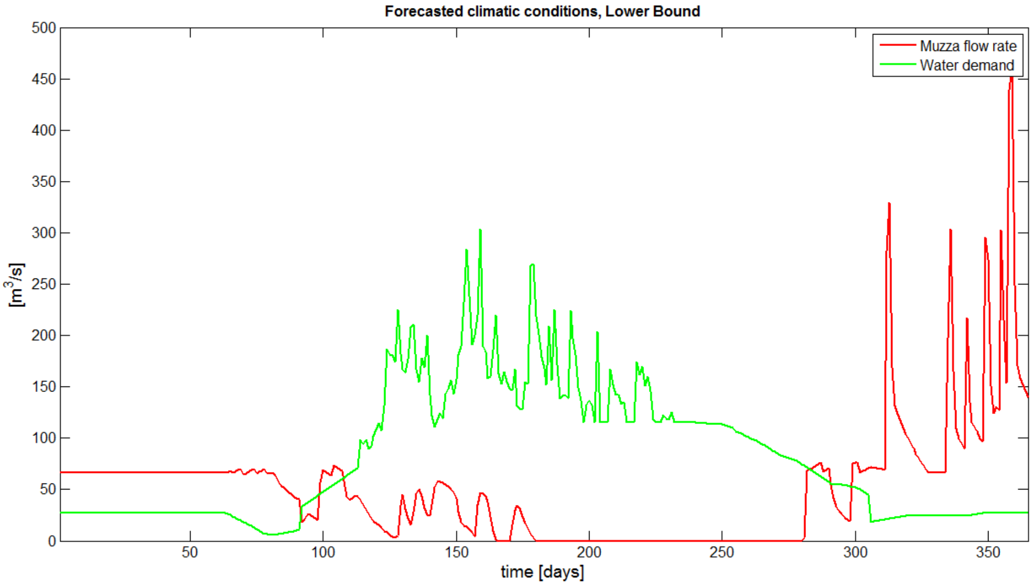

Figure 4.11: Comparison between average daily Muzza flow rate and water demand in the lower bound in forecasted climatic conditions.

Finally, the adaptation of the water supply is assessed by comparing the Muzza flow rates in the lower and upper bound: Figure 4.10 shows that the variation of the Muzza flow rate varies only slightly. Therefore, the Muzza canal is expected to dry out completely in the summer months. However, as visible in Figure 4.11, the water demand of the lower bound is high during those months and thus enormous deficits take place, whereas in the upper bound the water demand is null and thus crop production will not be impaired (see Figure 4.12). The complete drying of the Muzza canal is due to the assumption that in the Lake Como water system, the water availability to the Muzza district is the residual release that was not withdrawn by other irrigation districts. Thus, in moments when the release is smaller than the sum of other districts' water allowances, the Muzza canal cannot divert any water from Adda river. However, the actual mechanism to partition water among different irrigation districts is quite different. In addition, draining effects of Adda river from groundwater may take place. The evaluation of these aspect, despite being absolutely useful to enhance the representativeness of the results, requires to be investigated in more detail in the future developments of this work.

In summary, the difference between the supply and demand is really strong in the lower bound, whereas the water supply almost matches the demand in the upper

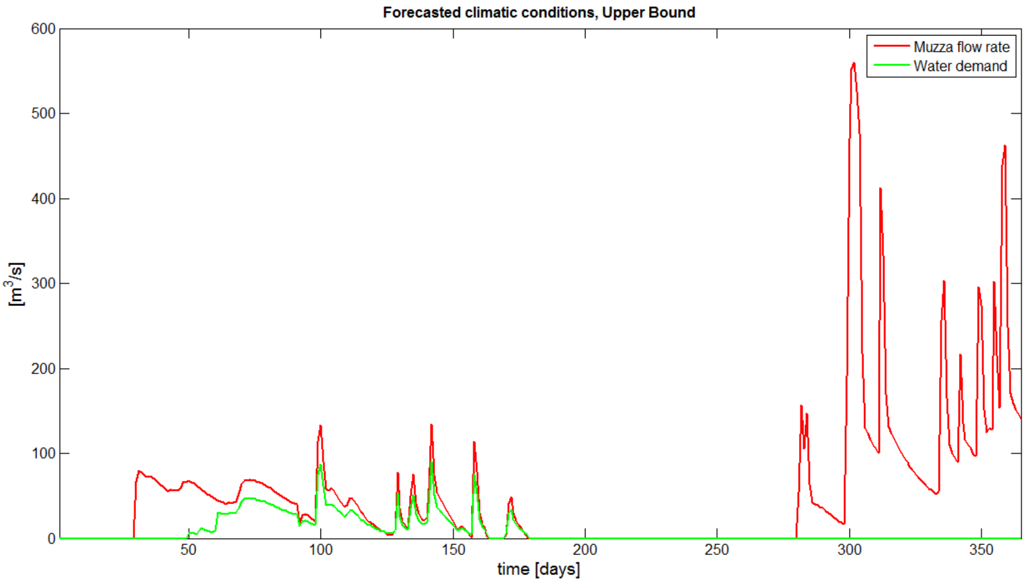

Figure 4.12: Comparison between average daily Muzza flow rate and water demand in the upper bound in forecasted climatic conditions.

bound. Thus the combined effect of farmers and water supply adaptation allows to accomplish great results even though the latter does not change significantly and hence does not appear to contribute much.

These results shown above prove the efficacy of co-adaptation strategies of farmers choices and water supply (and consequently of the methodology developed in this work) to mitigate climate change impacts on crop yields and farmers' agricultural practices.

4.4 Mitigation of climate change impacts

The results described in the two previous Sections are substantially different. This Section aims at identifying the main differences to clarify the role and potential impacts that climate change may have in the future and assessing the effectiveness of the Coupled Model in mitigating them. However, before entering this analysis, it seems interesting to highlight the variations of the main meteorological factors which influenced the results in the two climatic scenarios.

In Table 4.1 the values assumed by some fundamental meteorologic variables and averaged on the study area are listed. It is useful to remind that while the values of the current climatic conditions were actually measured by the 11 meteorological stations distributed on the space domain, the values referring to climate change conditions are instead the results of the downscaling procedure described in Section 3.4 and consist in an estimate of the climatic conditions characterizing the study area in the hypothesis of the worst emission scenario (A2).

Table 4.1: Meteorologic variables in the study area in current and climate change scenarios (T_{max}: daily maximum temperature $[C]$, T_{max}: daily minimum temperature $[C]$, P: daily precipitation $[\frac{mm}{day}]$, U_{mean}: average daily air humidity [%], V_{wind}: average daily wind speed $[m/s]$, NR: net radiation $[\frac{MJ}{m^2 \cdot day}]$).

	T_{max}	T_{min}	P	U_{mean}	V_{wind}	NR
$Average(CurrentConditions)$	18.83	7.62	2.47	77.90	1.32	79.37
$Maximum(CurrentConditions)$	39.68	24.63	162.80	100.00	7.91	214.34
$Average(ClimateChange)$	22.10	10.95	2.53	78.23	1.26	82.86
$Maximum(ClimateChange)$	47.17	30.22	145.70	100.00	8.06	196.57

From the data above, some interesting trends between the two climatic scenarios are visible, particularly with reference to the temperature and precipitation values, which are the variables that most affect crop production.

It is already common knowledge that average and annual maximum temperatures will tend to increase worldwide in the next decades due to climate change effects. The meteorologic data above are in accordance with this idea. T_{max} represents the daily maximum temperature, T_{min} the minimum. The average T_{max} and the maximum T_{max} during the year will increase by +3.27°C (+17%) and +7.49°C (+19%) respectively with respect to the current climatic conditions. The fact that the maximum T_{max} increases more than the average T_{max} means that extreme events can be expected more frequently and, along with them, an increase in the intensity of droughts and water shortages. The same trend characterizes the minimum daily temperature T_{min}. By glancing at the average distribution in time of T_{max} and T_{min} represented in Figures 4.13 and 4.14 respectively, it is quite visible that T_{max} will strongly increase during the whole year, with the highest peaks during summer

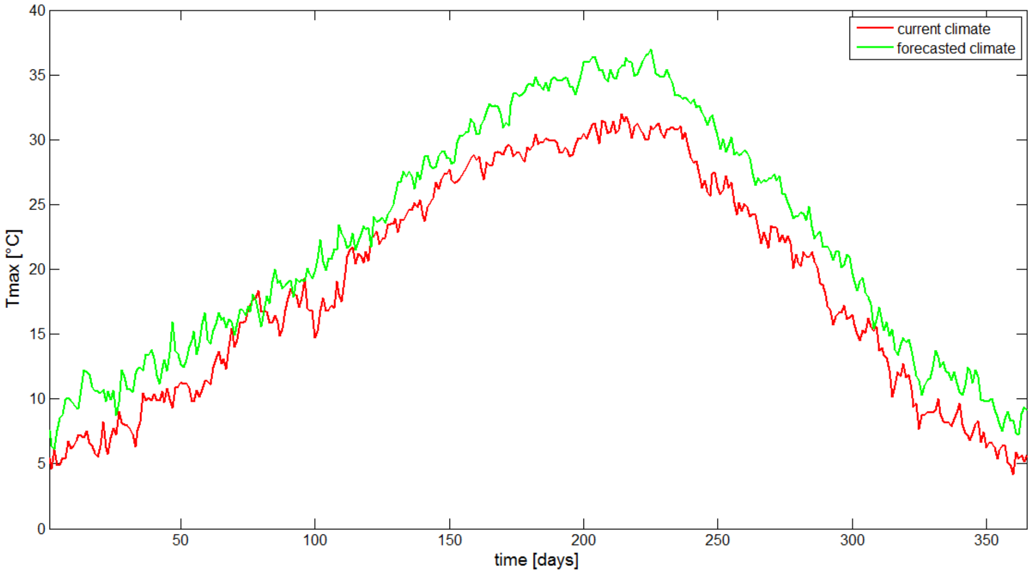

Figure 4.13: Average maximum daily temperature in current and climate change conditions.

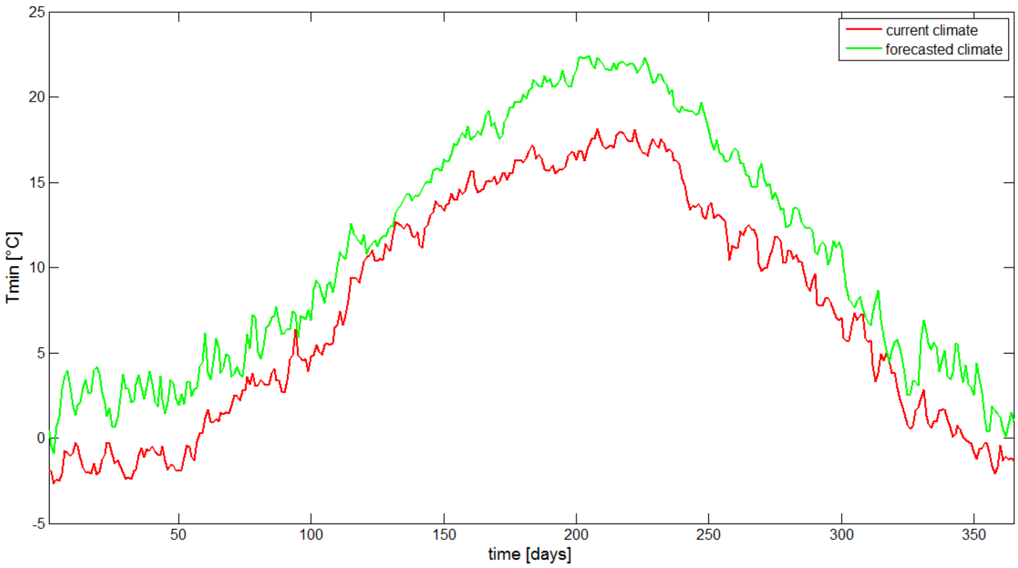

Figure 4.14: Average minimum daily temperature in current and climate change conditions.

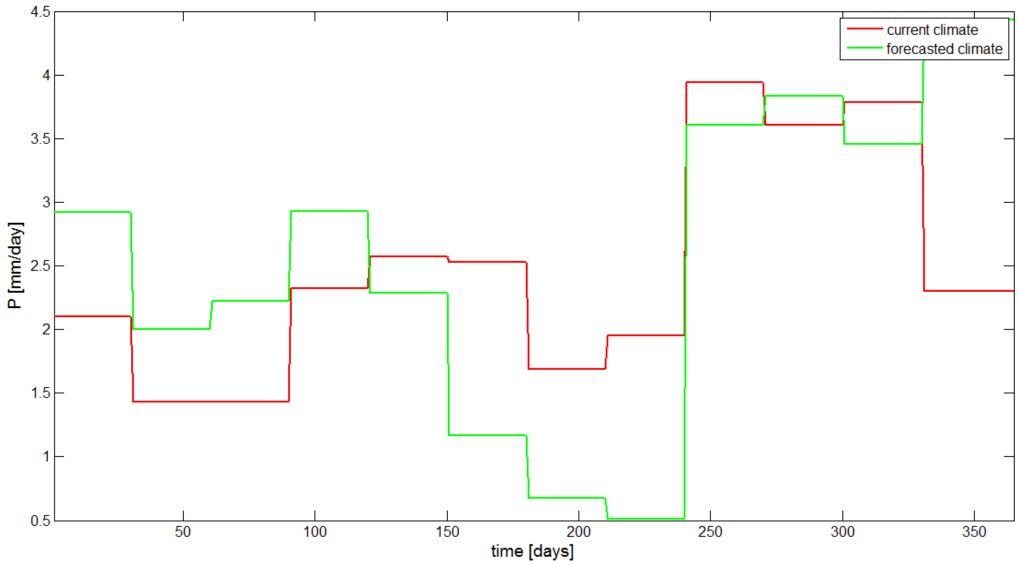

Figure 4.15: Average daily precipitation on a monthly basis in current and climate change conditions.

months; T_{min} will increase during the whole year as well, but the most remarkable differences with respect to the current climatic conditions will take place during winter, with values that will almost never go below 0°C.
It is interesting to highlight the effect of the higher temperatures on the sowing and harvesting dates summarized in the Table 4.2 for each of the considered crops. Higher temperatures allow to anticipate both sowing and harvesting dates. However, while the former can be anticipated only by a few days, the latter, thanks to strong increases of temperatures during the summer months, can be anticipated by even 46 days in the case of grass. The main consequence is a strong contraction of the growing season, which could allow farmers to plant a second crop at the end of the growing season: short-cycle crops, namely particular cultivars able to produce good harvests even in few months, could be sown just at the end of the first growing season. Nevertheless, a similar practice is already being chosen in some cases, even in the current climatic conditions: the annual rotation of short-cycle maize and winter cereals is in fact quite common. However, the increase of daily average temperatures may facilitate this option, making it possible even in regions where today it is not.

Table 4.2: Climate change-driven anticipation of sowing and harvesting dates for the different crops considered in this work.

	SugarBeet	*Tomato*	*Grass*	*Maize*	*Soybean*	*Rice*
Sowing anticipation	3	1	3	0	0	0
Harvesting anticipation	43	31	46	37	19	43

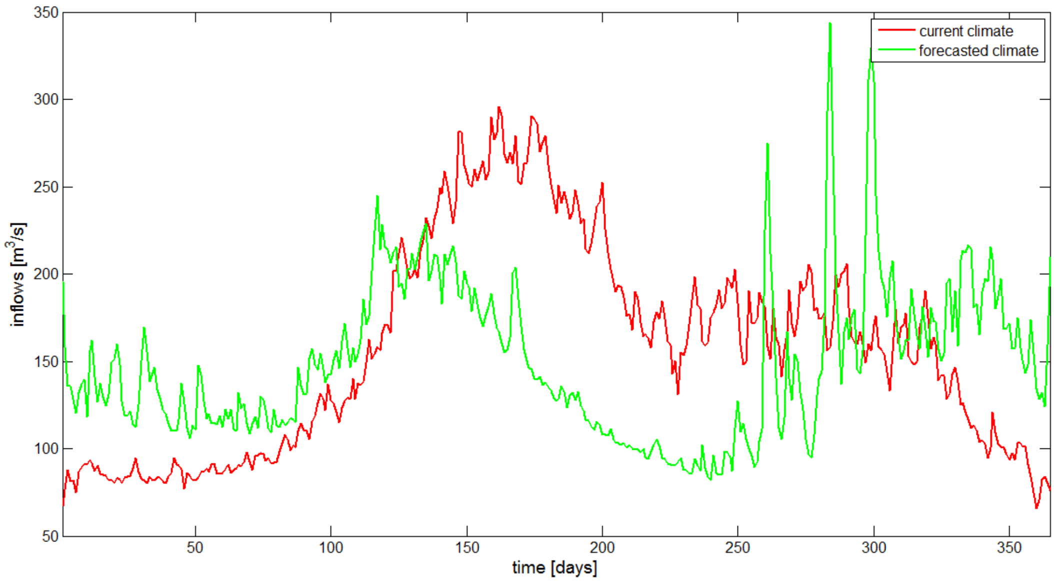

Figure 4.16: Variation of the daily average inflows to Lake Como from the current to the forecasted climatic conditions.

As far as precipitation values are concerned, Table 4.1 shows that the average conditions are more or less stable, but strong precipitations will probably tend to decrease in the forecasted conditions (-10.5% of precipitation peaks in extreme events) even though the precipitation peak during fall season which characterizes the typical pluviometric regime is expected to persist in the future. Figure 4.15 shows that the average daily precipitations during winter and spring will increase quite remarkably (mostly in December), but strong reductions will take place in late spring and summer, namely exactly during the growing season of agricultural activities. Thus, water supply will have to adapt in order to compensate these reductions and mitigate the impacts on crop production activities: in order to meet agricultural water

demands during summer months (when precipitations are expected to be very low), water will need to be stored in Lake Como as much as possible during winter and early spring. Nevertheless, this option would be incompatible with the gentlemen agreement currently existing between hydropower companies and farmers, according to which the regulation should be alternatively in favor of farmers during summer and hydropower companies during winter. However, this problem lies beyond the aims and purposes of this work and will be thus disregarded.
A final remark concerning the variation of relevant environmental variables between the two climatic scenarios considered is related to the inflow distribution during the year. As Figure 4.16 shows, the average daily inflows to Lake Como will change significantly. While in current climatic conditions the inflow peak is unique and takes place between May and June (just before the most water stress sensitive crop growth stages), in the forecasted climatic conditions two peaks will happen, one in the early spring (March-April) and one in autumn. A strong reduction of the average inflows is instead expected during the main growing season (from June to August), proving once more the relevance of water supply adaptation to mitigate the potential negative effects on crop production activities.

4.4.1 Climate change impacts assessment: lower bound

The main goal of this Section is to identify the potential impacts that climate change would cause on the case study water system if no adaptation took place by either farmers or Regulator (lower bound). Thus, the results of the lower bound in the two different climatic scenarios will be compared.
Given the same crop choice pattern (maize and permanent grass), the average daily water deficit in current climatic conditions is $15.67\frac{m^3}{s}$, whereas in the forecasted ones equals $39.69\frac{m^3}{s}$. This result clearly shows that if no adaptation takes place average water deficits during the year could possibly increase by more than 250% before the end of this century. However, this datum is absolutely optimistic. Figure 4.17 shows that the biggest increase in water deficits will take place in late spring and summer: if we thus focus on this period, the average daily water deficit in current climatic conditions will be $21.06\frac{m^3}{s}$ and will increase to $85.23\frac{m^3}{s}$ (+405%), leading to strong water stresses during the growing season and thus reduced crop productivity at the end of the year. Crops showing a high sensitivity to water stresses (e.g. tomatoes

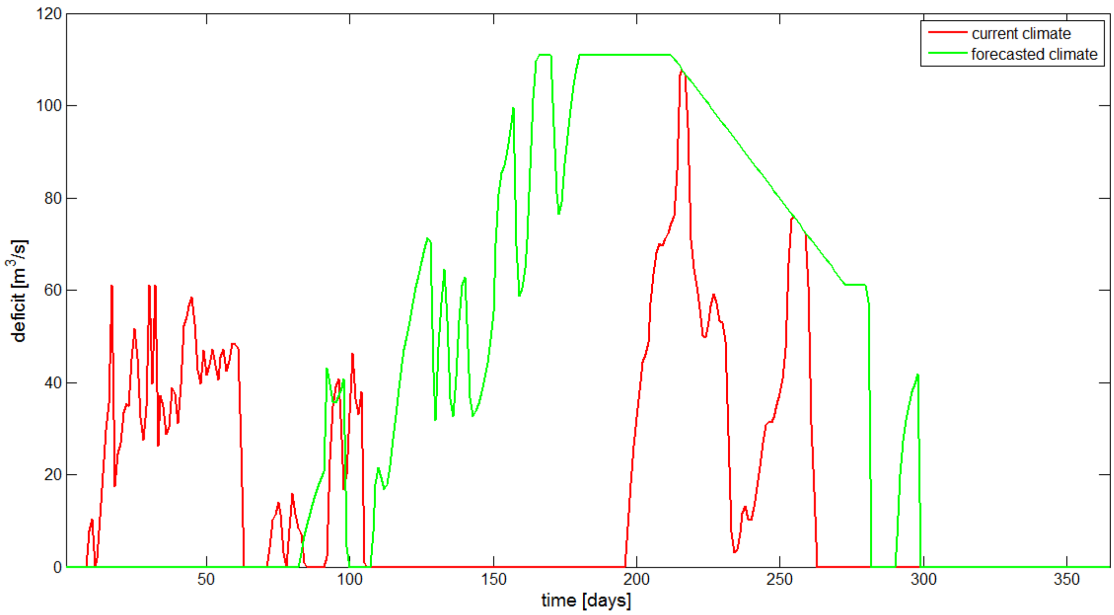

Figure 4.17: Difference between water deficits in current and forecasted climatic conditions if no adaptation takes place (lower bound).

and maize), even though highly profitable, could tend to disappear if no adaptation strategies are implemented to counteract climate change impacts.
Another relevant observation concerns the water availability in the Muzza canal. If no adaptation takes place by the Regulator, the Muzza canal will be completely dry for almost the whole growing season (from June up to September) while the water demand is still high (see Figure 4.11). This effect could cause strong yield reductions or even the complete loss of the harvest.
In conclusion, a worsening of the climatic conditions in which agricultural activities have to operate is expected over the next century. The effects of climate change on water availability and agricultural activities could be ominous if no adaptation strategies are developed and implemented: not only the most profitable crops will tend to disappear, but also the most resistent to water stresses will incur in potentially strong yield reductions.

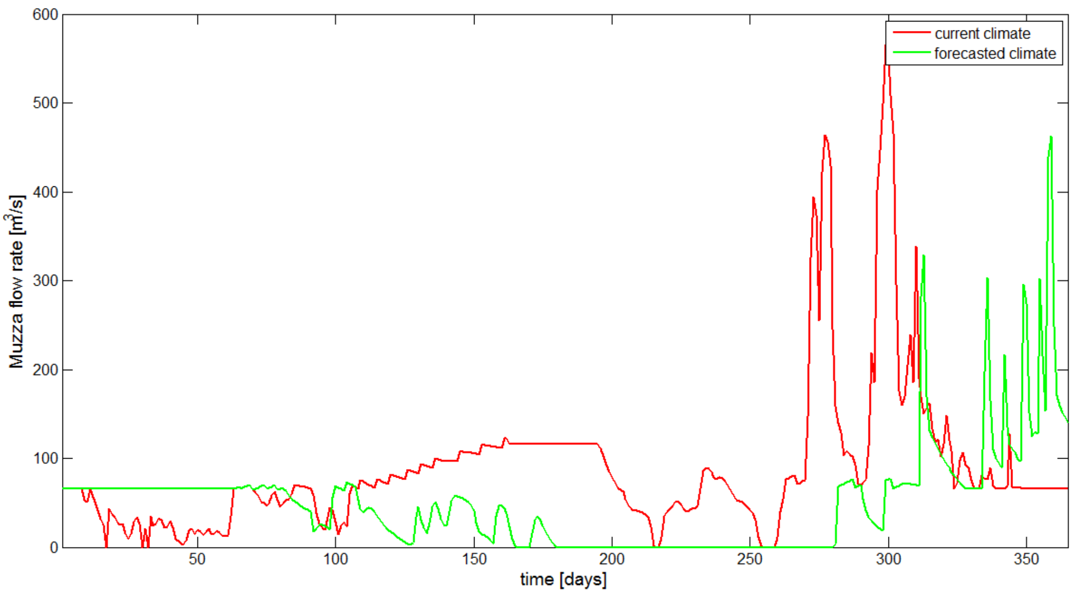

Figure 4.18: Difference between the water flow rate of the Muzza canal in current and forecasted climatic conditions if no adaptation takes place (lower bound).

4.4.2 Climate change impacts assessment: upper bound

This Section is aimed at showing the impacts of climate change on agricultural production activities if adaptation strategies are implemented (upper bound). The results shown in the previous Sections already highlighted the effectiveness of adaptation strategies in mitigating climate change impacts, given a certain climatic scenario. However, the comparison of the upper bounds referring to the two climatic scenarios considered in this work allows to highlight how the effectiveness of adaptation strategies varies in two different time periods.

The first basic consideration is that adaptation is accomplished by means of a strong shift of the crop choice pattern: farmers change their crop choice from tomatoes in the current climatic conditions to mostly permanent grass in the forecasted scenario, namely from a highly water consuming to a less demanding crop typology.
Given this crop choice shift, the average daily water deficit is $0.16\frac{m^3}{s}$ in the current climatic conditions and $1.07\frac{m^3}{s}$ in the forecasted ones (+670%). In addition, Figure 4.19 shows that the most relevant water deficits will take place in forecasted climatic conditions earlier than in the current ones. As concerns the water supply, the adap-

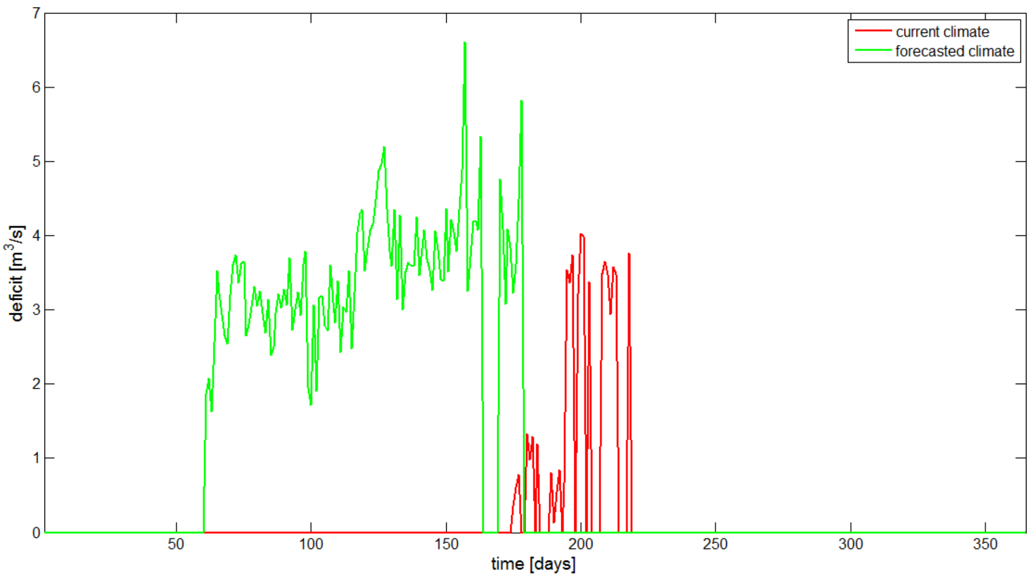

Figure 4.19: Difference between water deficits in current and forecasted climatic conditions if adaptation takes place (upper bound).

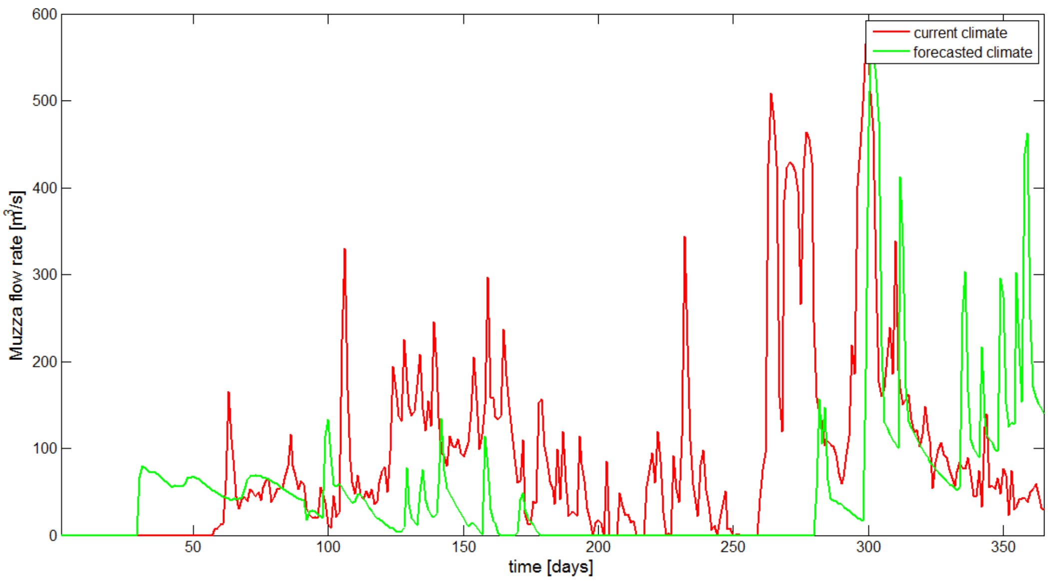

Figure 4.20: Difference between the water flow rate of the Muzza canal in current and forecasted climatic conditions if adaptation takes place (upper bound).

tation measures are evident. As portrayed in Figure 4.20, a strong redistribution of water availability during the year is applied.

Two conclusive considerations seem relevant to complete the assessment of climate change impacts.
The first observation is based on the comparison between lower and upper bound: if no adaptation strategies are implemented the average annual water deficits will increase from $21.06\frac{m^3}{s}$ in current climatic conditions to $85.23\frac{m^3}{s}$ in forecasted climatic conditions, whereas if farmers and water supply adapt to climate changes the increase of water deficits will be from $0.16\frac{m^3}{s}$ to $1.07\frac{m^3}{s}$. It is possible to conclude that the adoption of adaptation measures allows to reduce strongly the impact of climate change.
Finally, it is interesting to notice that the average water deficit caused climate change in the upper bound ($1.07\frac{m^3}{s}$) is still remarkably lower than the average water deficit of the lower bound in the current climatic conditions ($15.67\frac{m^3}{s}$), meaning that the negative impacts of climate change do not even nearly compensate the beneficial effects of the implementation of adaptation strategies.

Chapter 5

Conclusions

The continuous growth of food demand is forcing agricultural activities to exploit environmental resources more and more intensively. Water availability has already become a limiting factor for agricultural production and thus water saving practices need to be implemented to reduce water wastage. In this direction, some possible options, e.g. upgrade of the irrigation technique and Best Management Practices implementation for moisture retainment, can be independently adopted by farmers. The possibility that this work aims to explore is instead a re-optimization of the water supply to match the actual water demand of downstream irrigation districts. Nowadays, in fact, Regulators plan the releases from the reservoirs on the basis of a fixed water allowance that is guaranteed by regulation to downstream users. Release plans are thus unable to account for the evolution in time of agricultural activities and possible related variations of farmers' actual water demands and, as a consequence, a strong inefficiency characterizes them.
The second fundamental issue addressed by this work concerns the assessment and mitigation of climate change impacts. In fact, the current inefficiency of operating policies in meeting the needs of downstream users is very likely to increase over the next century. Climate change will bring about an increase in the frequency and magnitude of extreme events, among which water shortages, droughts and high temperatures. To effectively face a changing climate, the development and implementation of adaptation strategies are essential: farmers' annual planning should detach from the traditional crops' choices and instead select the most profitable crops to plant according to the forecasted climatic conditions; as concerns the water supply management, the regulated water allowances should be replaced by the estimated actual water demand in the operating policy design phase. In literature,

there exist several studies which addressed the two problems separately: some of them focus on the water supply management and simulate the adaptation of operating policies to climate change on the basis of a given estimate of the downstream water demand; some other studies, on the opposite, assume a fixed water supply and test farmers' adaptation under some forecasted climatic scenarios.
The main goal of this work is to develop a new methodology to integrate supply and demand problems by means of an information loop: farmers solve a yearly planning problem to decide the most profitable crop to plant and, on the basis of the deriving water demand estimate, water supply is optimized. Then, the exchange of expected irrigation demand and supply is repeated until convergence is reached. Projected hydro-climatic scenarios are used as boundary conditions to the loop.

The effectiveness of this methodology was tested on a real-world case study, namely the Lake Como which serves the Muzza-Bassa Lodigiana irrigation district (Italy). In the current climatic conditions, the integration of farmers and Regulator decision-making processes by means of the information loop accomplished a strong reduction of water deficits frequency and magnitude. This allowed all farmers of the district to shift their production choice from maize and grass to tomato, a highly profitable but also sensitive crop. In the forecasted climatic conditions, the methodology developed in this work allowed to achieve similar results as concerns water deficits. The most relevant result is however related to farmers' adaptation to climate change impacts, which led most of them (65 over 66 agents) to shift their crop choice from tomatoes to permanent grass. Finally, it was proven that climate change is very likely to cause substantial increases in water deficits and, consequently, crop yields reductions if no adaptation measures are implemented by neither farmers nor water supply. If, on the opposite, a positive response is developed, climate change impacts can be remarkably mitigated: some increases in water deficits are still likely to take place even if co-adaptation of farmers and water supply takes place, but the risk of complete loss of the harvest will be strongly reduced.

In conclusion, the results achieved prove very clearly the efficacy of the methodology developed in this work to abate crop water stresses and thus increase crops' productivity both in current and projected climatic conditions. The proposed approach represents a promising start towards the enhancement of water resources exploitation efficiency for agricultural purposes and the assessment of the efficacy of farmers and water supply management adaptation measures to climate change impacts. However, many aspects of the proposed approach require further investigations. Future directions of investigation might be the following:

- implement an advanced optimization algorithm (i.e. genetic algorithm) to allow the crop choices to be taken at cell level, rather than irrigation unit level;
- add crop production costs to upgrade farmers' objectives from income to profit;
- increase the size of farmers choices feasibility set, by adding:
  - other crops (e.g. winter crops) in addition to those considered in this study and the possibility to split the growing season between different crops (particularly in forecasted climatic conditions);
  - the possibility to upgrade irrigation techniques to more efficient ones;
  - the possibility to implement management actions (e.g. fertilizers and pesticides application) and Best Management Practices;
- develop reasonable constraints to limit farmers' choices of each crop (e.g. constraints defining the maximum amount of each crop that industries can process);
- study the possibility of including a model of crop prices in order to generate more representative and realistic socio-economic scenarios as input to the FDMP;
- refine the crop growth model by accounting for crops' stage-dependent sensitivity to water stresses, e.g. by modifying the values of yield response factor and harvest index on the basis of the moment in which the main water stresses took place, and thresholds of yield reductions below which the harvest can be considered completely lost (if the harvest is too low with respect to the potential one, the quality of the harvested biomass is low and thus crops cannot be sold);
- define more realistic sharing rules among different irrigation districts than those used in the case study, and possibly extend the analysis from a single to multiple irrigation districts;

- study the hydrologic relationship between Adda river and the groundwater system, in order to account for possible water recharges or losses along the path from the regulated dam to the canal intake of each irrigation district;
- conduct a sensitivity analysis to assess the relevance of the different assumptions made in this work (model diagnostics).

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