System dynamic approach to evaluate socio-economic-environmental factors influencing sustainability of water use in agricultural production

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LIBERATORIA PER L'ARCHIVIAZIONE DELLA TESI DI DOTTORATO

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del Politecnico di Bari

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iscritto al 3° anno di Corso di Dottorato di Ricerca in RISCHIO, SVILUPPO AMB. TERRITORIALE ED EDILIZIO ciclo XXX

ed essendo stato ammesso a sostenere l'esame finale con la prevista discussione della tesi dal titolo:

SYSTEM DYNAMIC APPROACH TO EVALUATE SOCIO-ECONOMIC-ENVIRONMENTAL FACTORS INFLUENCING SUSTAINABILITY OF WATER ~~RESOURCE~~ USE IN AGRICULTURAL PRODUCTION

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Approccio basato sulla teoria della dinamica dei sistemi complessi per valutare i fattori sociali-economici-ambientali che influenzano l'uso sostenibile delle risorse idriche nella produzione agricola

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Final Dissertation

System dynamic approach to evaluate socio-economic-environmental factors influencing sustainability of water use in agricultural production

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A Daniele,
per la pazienza che ha avuto
nel seguirmi ed incoraggiarmi
in questo percorso così lungo.

EXTENDED ABSTRACT

Irrigated agriculture plays a vital role for socio-economic development of the Mediterranean area, although it is the largest exploiter of both water and energy resources. Given its importance, in a context in which water resources experience increasing pressure due to different global challenges (i.e., climate change, growth population and economic development among others), there is an urgent need of sustainable management of irrigation water resources. Nevertheless, it is extremely challenging, especially at the local scale, due to several complex and interconnected dynamics establishing in a given irrigation system. In such systems, multiple actors are indeed involved in decision-making processes, and the use of natural resources strongly depends on their behaviors affecting the dynamics of the system itself. As result, facing sustainable management of water resources issues through only a technical knowledge is not enough. Whereas, a careful knowledge of the system and its dynamics is essential for supporting a sustainable management of water resources. For the above reasons, integrated approach are needed for dealing with holistically water management issues. Among the recent integrated approaches developed in scientific literature the Water-Energy-Food Nexus is surely an useful methodology for supporting sustainable management of water resources by studying complex linkages among resources and integrating management and governance across sector and scale. In order to holistically evaluate sustainable resource management, this study proposes an innovative integrated methodology capable to operationalize the Water Energy Food Nexus (WEFN) at local level evaluating the multi-dimensional implications of irrigation use by identifying the main factors controlling the selection and exploitation of water sources. In detail, a model based on Causal Loop Diagrams (CLD) was implemented in a case study, used as reference, located in Southern Italy in order to get a deeper insight into a complex irrigation system. Moreover, three sustainability indices based on the “footprint” concept were defined in order to quantify the multidimensional implication of irrigation practice. Firstly, the Irrigation Water Footprint Index aims to evaluate the impacts of irrigation use on the available water resources of a given area. Secondly, the Energy Footprint for Irrigation Index quantifies the amount of energy consumed for water withdrawals and pumping, compared to the unit crop revenue. Finally, the Irrigation Water-Cost Footprint Index supports the evaluation of the economic benefits of agricultural production, compared with the costs of water for irrigation. All indices can be expressed both in an aggregated and disaggregated form to assess the impacts and benefits related to the use of specific water sources. Moreover, the integration of the aforementioned approaches is also proposed as the innovative element for supporting the sustainable management of water resources. Indeed, indices are important instrument to quantitatively evaluate the state of resources exploitation, but they reveal little of a given irrigation system dynamics, which are essential to quantify for identifying the effectiveness of a given sustainability policy. The obtained results reveal some general conclusions. As first finding, a dense network of relationships among different decisional actors involved strongly influence the dynamic of the system. Moreover, it is clear that actor behaviors is affected by external drivers (i.e., crop market price and water availability) and internal constraints (e.g., water tariff). At the end, the mid-long time effectiveness of a given policy is affected by system dynamic.

key words: *Water-Energy-Food Nexus, System analysis, Sustainable management of irrigation water resource*

SOMMARIO

Sebbene l’agricoltura irrigua sia ritenuta una delle principali fonti di sfruttamento di entrambi le risorse idriche ed energetiche, è’ ampiamente accettato che essa svolge un ruolo fondamentale per lo sviluppo socio-economico di molti paesi dell' area mediterranea. Data la sua importanza, in un contesto in cui le risorse idriche sono sempre più soggette a pressioni crescenti a causa delle diverse sfide globali (ad esempio, il cambiamento climatico, la crescita demografica e lo sviluppo economico), vi è urgente necessità di gestire in maniera sostenibile le risorse idriche destinate a scopi irrigui al fine di garantire elevate rese produttive. Tuttavia, le dinamiche complesse che si instaurano all’interno di un sistema di gestione idrica ad uso irriguo rendono la gestione sostenibile delle risorse idriche di difficile attuazione. Tali sistemi, infatti, sono caratterizzati da un elevata complessità dovuta al comportamento di numerosi attori da cui l’utilizzo di risorse naturali dipende e che influisce sulla dinamica del sistema stesso. Non basta, dunque, guardare solo agli aspetti quantitativi dell’utilizzo di risorse idriche (e.g., impatti ammbientali), ma, al fine di supportare la loro gestione sostenibile, è indispensabile anche un’attenta conoscenza del sistema e della sua dinamica. Da qui deriva, la necessità di affrontare le problematiche della gestione delle risorse idriche in maiera olistica mediante approcci integrati e multidisciplinari.

Tra gli emergenti approcci integrati e multidisciplinari, in ambito scientifico si è affermato recentemente il paradigma del nesso tra Acqua-Energia-Cibo, che si configura come un adeguata metodologia capace di supportare la gestione sostenibile delle risorse idriche attraverso l’analisi dei complessi legami tra le risorse naturali integrando gli aspetti gestionali della risorsa su scala intersettoriale.

Partendo da queste premesse, al fine di affrontare olisticamente le problematiche della gestione sostenibile delle risorse idriche ad uso irriguo, il seguente studio di ricerca propone una metodologia innovativa e integrata in grado di operazionalizzare il paradigma di Acqua-Energia-Cibo a scala locale. In particolare la metodologia implementata è in grado di valutare le multi-implicazioni dell'uso dell'acqua irrigua attraverso l'identificazione dei principali fattori che influiscono sul prelievo e lo sfruttamento delle risorse idriche. Per cui, al fine di studiare le dinamiche che si instaurano in un sistema di gestione idrica ad uso irriguo, è stato implementato un modello concettuale attraverso l'utilizzo di diagrammi causa-effetto (i.e., Causal loop Diagrams), considerando un caso di studio rappresentativo situato al Sud Italia nella regione Puglia. Tale analisi ha consentito la conoscenza e la definizione dei confini sociali ed ambientali del sistema considerato indispenzabile per la definizione degli indicatori di sostenibilità rappresentativi della dinamica del sistema. Dunque, tre indici di sostenibilità basati sul concetto di "impronta" sono stati definiti per quantificare l'implicazione multidimensionale della pratica irrigua. In primo luogo, l'Indice di "Impronta idrica ad uso irriguo" mira a valutare l'impatto dell'uso dell'acqua irrigua sulle risorse idriche disponibili di una determinata area. In secondo luogo, l'Indice di "Impronta Energetica per l'irrigazione" quantifica la quantità di energia consumata per i prelievi e il pompaggio dell'acqua rispetto ai ricavi unitari delle colture. Infine, l'Indice di "Impronta economica" permette la valutazione dei benefici economici della produzione agricola rispetto ai costi dell'acqua utilizzata per l'irrigazione. Tutti gli indici sono stati espressi sia in forma aggregata che separata al fine di valutare gli impatti e i benefici legati all'uso di specifiche fonti idriche quali ad esempio superficiali e sotterranee.

Infine, l'integrazione degli approcci di cui sopra viene inoltre proposta come elemento innovativo del seguente lavoro di ricerca, per supportare la gestione sostenibile delle risorse idriche. Difatti, gli indici rappresentano uno strumento importante per valutare quantitativamente lo stato dello sfruttamento delle risorse, ma rivelano poco della dinamiche di un dato sistema irriguo, la cui conoscenza è indispensabile per valutare l'efficacia dell'implementazione di una data politica di sostenibilità.

I risultati ottenuti consentono di trarre alcune conclusioni generali dettagliatamente spiegate nei seguenti capitoli di tesi. In primo luogo, la fitta rete di relazioni tra i diversi attori decisionali coinvolti influenza fortemente la dinamica del sistema. In secondo luogo, i comportamenti degli attori sono influenzati sia da fattori esterni (prezzo di mercato del raccolto e disponibilità idrica) che da vincoli interni (ad esempio, tariffe idriche). Infine, l'efficacia a medio-lungo termine di una determinata politica è influenzata dalla dinamica del Sistema. Pertanto l'integrazione tra aspetti qualitativi della dinamica del sistema con gli aspetti quantitative di utilizzo di risorse idriche si è rivelata di fondamentale importanza per conoscere l'efficacia dell'implementazione di una plausibile politica di sostenibilità nel breve, medio-lungo termine.

Parole chiave: *Nesso Acqua-Energia Cibo, Analisi del sistema, Gestione sostenibile delle risorse idriche irrigue*

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INTRODUCTION

"I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me"

Isaac Newton

Despite being widely recognized that irrigated agriculture plays a crucial role in worldwide socio-economic welfare, it is likewise agreed that it is the largest exploiter of water resources (FAO, 2014), since the majority of freshwater withdrawals (around 70%) are used to produce food (FAO, 2012). At the same time, due to the unquestionable link between water and energy resources, high amounts of energy consumption are associated with freshwater supply (Sishodia *et al.*, 2016). For example, in 2014, about 4% of the global electricity consumption was used to extract, distribute and treat water and wastewater, while 50 million tons of the oil equivalent of thermal energy (mostly diesel) were used for irrigation pumps and gas for desalination plants (IEA, 2016). Although global scale analyses estimated that the actual water availability exceeds the demand for freshwater resources (Sophocleous, 2004), they are expected to experience increasing pressures in the imminent future due to the increasing food demand, which in turn influence the amount of energy consumed. Going in further detail, the Intergovernmental Panel on Climate Changes estimated that the expected warming coupled with the variability of the spatial distribution of precipitation will result in increase of annual average river runoff and water availability at high latitudes and in some wet tropical areas (IPCC, 2014). Whereas at mid-latitudes and in the dry tropics it will result in their decreasing. Consequently, many semi-arid and arid areas are particularly exposed to the impacts of climate change and are expected to suffer a decrease of water resources due to this (Bates *et al.*, 2008). In addition to the climate change effects, due to the clear link among water and food, growth population, changing in life style and eating habits, and economic development contribute to affect water sector by increasing food demand (Godfray *et al.*, 2010) with cascading negative impacts on the environment. For example, in most of the arid and semi-arid regions, the spread of intensively irrigated agricultural areas has led to a dramatic increase in water demand resulting in groundwater overexploitation, causing an impoverishment of water quantity and quality.

For facing such challenges, preventing the ecosystem from further damages, the concept of *sustainable management of irrigation water resources* was developed and a growing number of studies of the last few decades tried to operationalize it (Raju, Duckstein and Arondel, 2000; Aldaya, Martínez-Santos and Ramón Llamas, 2010; United *et al.*, 2013; Donoso *et al.*, 2015; Mekonnen *et al.*, 2015; Sala, Ciuffo and Nijkamp, 2015). However, due to the openness of this concept, several interpretations exist in literature as detailed explained in the following chapter. Nevertheless, the analysis of the different interpretations highlights that considerations on purely technical criteria are no longer sufficient to address the complicated challenges facing the water management issues (Pahl-wostl *et al.*, 2007; Juwana, Muttil and Perera, 2012). As per Mays, (2013), water use affects numerous many aspects of our existence with so many facets that must be considered in a sustainability assessment. This is particularly relevant for irrigation water resources for which sustainable management requires a deep knowledge of the system complexity. This is due to the fact that multiple actors are involved in an irrigation water system and complex, and interconnected loops among them strongly affect its dynamic (Giordano, Brugnach and Pluchinotta, 2016).

In such system, as indicated in Portoghese et al., (2013) and Giordano et al., (2015), management strategies based on a technical and poor knowledge of the system complexity may often be affected by a high uncertainty and result ineffective in their impacts. To overcome this problem, integrated and multidisciplinary approaches become essential for supporting sustainable management of irrigation water resources (Pahl-Wostl 2002) spamming among and across ecological and socio-economic domains. Particularly, adopting a holistic approach is essential for i) analysing the intertwined linkages among resource exploitation and ii) integrating management and governance across sectors and scales (Payen, Basset-Mens and Perret, 2015; Avellán *et al.*, 2017; EL-Gafy, Grigg and Waskom, 2017).

Among the recently developed paradigm for the integrated approach supporting the sustainable management of irrigation water resources, the Water-Energy-Food Nexus (WEFN), introduced by Hoff (2011), provides an useful approach able to support the transition process towards sustainability (Halbe et al. 2015). Following the definition provided by FAO (2014), the nexus perspective allows to analyse the complex linkages among resources and their usage, that need to be captured to avoid shifting problems from one sector to another. Bach et al. (2012) argue that unlike previous approach (e.g., Integrated Water Management Resource) the WEFN shifts the focus from water to its interaction with the other two resource (Giupponi, Gain and D'Odorico, 2015) considering the three aspects of water, energy and food as equally important. In this context, inter-disciplinary research focussed on the WEFN paradigm (physical, agro ecological, social sciences, economics) aids in linking different fields (e.g., energy and water) and in recognizing the importance of preserving ecosystem integrity and its link with local people's well-being. Several studies on the WEFN paradigm were thus developed in the last decades (e.g., Hoekstra and Mekonnen, 2008; Chapagain and Orr, 2009; Ercin et al., 2013; Donoso et al., 2015; Chukalla et al., 2015; Mekonnen et al., 2015). Nonetheless, such approaches highlight the multi-scale character of social-ecological processes, the high uncertainty that large-scale processes generate in the management practice, and thus the importance of focusing on local processes for facilitating the adaptive management cycle (Maass, 2017). Despite the recent developments of tools and techniques supporting "global" WEFN analyses, there is an increasing need for tools operating at a "local" level, which is the most policy-relevant scale (M Brugnach, Craps and Dewulf, 2014).

Moving from such premises, this study proposes a methodology capable to operationalize the WEFN evaluating the multi-dimensional implications of irrigation use by identifying the main factors controlling the selection and exploitation of water sources. For this purpose, the complexity charactering the dynamic of a local irrigation water management system is analysed and then integrated with an index-based approach for supporting the decisional process of sustainable management of water resources. Going in further details, first a conceptual model has been developed to study the complex dynamism of irrigation water system. The analysis of the system's dynamic allows to identify the key aspects that may influence sustainable management of water resource. At the same time, in order to describe the multi-dimensional implications of water use, three indices and three different sub-indices are defined for estimating i) the environmental sustainability of water use for irrigation, ii) the economic profitability of irrigation practices known the water costs associated to suitable water sources and the land productivity (i.e., cost/benefit), and iii) the source-to-field energy consumption related to irrigation practice. It is worth nothing that the index-based approaches is an important tool to quantitatively evaluate the state of resources exploitation, since its outcomes aid to synthetize information. Nevertheless, as this study tries to demonstrate, for supporting the decision making of sustainable management of water resources, the integration of the above analysis is crucial to evaluate the effects that the implementation of a given policy may have on the system. In this framework, the main element of innovation of the proposed methodology is related to the capability of joining the qualitative aspects of complex system operating at regional scale with the quantitative implications of the water resources use. Thus, this study try to answer the following research questions:

1. Which are the main factors conditioning the sustainable management of water resources?
2. Which are their impacts on system dynamic?

3. Which are the impacts on the irrigation water system of a given policy implementation?

CHAPTER 1

SUSTAINABLE MANAGEMENT OF WATER RESOURCES: EVIDENCE, PRINCIPLES AND ASSESSMENT

> “*We cannot solve our problems with the same thinking we used when we created them*”
>
> *Albert Einstein*

1.1. Sustainable development, Water management and Water Resources Sustainability Principles

Although *sustainability* concept is largely used in several fields (e.g. economic, environmental, social, …), its meaning is vague and open to many different interpretations. Therefore, several definitions of sustainability exist.

The concept of sustainability emerged in 1987 when Brundtland Commission introduced the concept of *sustainable development* defining it as a development process that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987). Specifically, it is configured as a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and the institutional change need to be made consistent taking into account the future as well as the present needs (Brundtland, 1987). Since 1987, sustainable development has become the focus of discussions and debates throughout the world and the concept was followed by other different interpretations such as:

> …*to maximize simultaneously the biological system goals (genetic diversity, resilience, biological productivity), economic system goals (satisfaction of basic needs, enhancement of equity, increasing useful goods and services), and social system goals (cultural diversity, institutional sustainability, social justice, participation)*.(E.B. Barbier, 1987)

> …*meeting human needs while conserving the Earth's life support systems and reducing hunger and poverty*. (Palmer *et al.*, 2005)

Even though the above definitions are applied in different context, they interpret the sustainability in similar manner highlighting some significant principles. Specifically, according with Juwana et al. (2012), each of them urges human actions to concern about present and future environments, while, at the same time, utilising natural resources to fulfil human needs. Whereas Brundtland's definition focuses on the balance of present and future generations, the other two ways for defining the sustainable development further address the need of concern for environmental, social and economic interests.

In line with the above interpretations, a growing number of studies further explore the concept of sustainable development focussing on the sustainability principles.

One of the most well-known sustainability principles is the "*triple bottom line approach*" released from the business world, originally introduced by John Elkington, a management consultant (Elkington, 1997). It is an accounting framework made by the interaction of three different pillars of sustainability related to environmental, economic and social aspects.

With the end of labelling different challenges, Spangenberg (2004) proposed a similar approach defining the "*prism of sustainability*" (see Fig. 1). From his point of view, three main challenges are identified:

i) the environmental challenge emphasising the degradation of natural resources for human use;

ii) the social challenge highlighting the unequal distribution of wealth and poverty;

iii) the institutional challenge focusing on peace and security.

As results, the prism reflecting sustainability principles, has four dimensions each of which is further explored in order to identify relevant indicators. For example, in case of the institutional dimension, the sustainability indicators are participation, justice and gender balance. For the environmental dimension, resource use and state indicators are identified. For the social dimension, the indicators are health care, housing, social security and unemployment. Finally, for the economic dimension, the indicators are Gross National Product (GNP), growth rate, innovation and competitiveness. Moreover, the prism of sustainability allows also at identifying the inter-linkage indicators between dimensions. The inter-linkages can be two, three or even four dimensional, which seek to compromise and synergise dimensions as shown in Fig. 1.

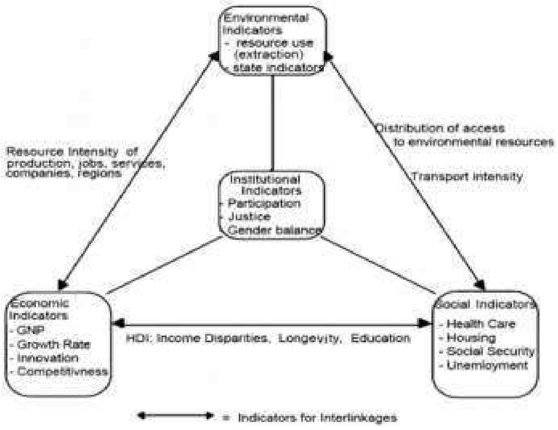


Figure 1: The prism of sustainability (Spangenberg and Bonniot, 1998)

An equivalent concept is the capital flow notion as introduced by Parkin (2000) which states that any process for achieving sustainability needs to manage different capital flows. Specifically, five capital flows were identified: natural, human, social, manufactured and financial. Any development proposal has to contribute to improving, or at least maintaining, these capital flows (Parkin, 2000).

As the complexity of the issues related to the water management increased, several studies combined the principles of sustainable development with the water management issues. In that framework, the concepts of *water resources sustainability and sustainable management of water resources has been developed.* Infact, both of the two concepts present equivalent meaning and are enlightened by sustainability principles. Nonetheless, similarly to the sustainable development, several definitions exist for defining the abovementioned aspects. For example Loucks, (2000) defines the concept of sustainable management of water resources referring to a water system designed and managed to fully contribute to the objectives of society, now and in the future, maintaining their ecological, environmental, and hydrological integrity. Whereas, Hjorth and Bagheri (2006) refer to the water system as a sub-system of the whole ecosystem, defining water sustainability as the way in which this sub-system behave having as purpose the sustainable development of the whole ecosystem. Following their point of view, three different dimensions related to environment, society and economy characterize water resources sustainability. Mays (2013) define water resources sustainability "*the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the damages brought about by natural and human-caused disasters that affect sustaining life.*" Moreover, as claimed by Mays (2013), water use affects so many aspects of our existence that must be considered in sustainable management of water resources. The need for the integration of water-related issues is also noted by Loucks & Gladwell (1999), which state that water sustainability can no longer be emphasised from a purely technical view, ignoring social and economic concerns.

The analysis of the above definitions of sustainability allows at deriving few general conclusions:

I. Considerations on purely technical criteria are no longer sufficient for supporting sustainable management of water resources, while an increased understanding of the interactions between nature and society is required;
II. Sustainable management of water resources is not only related to environmental issues but also the economic and social aspects are need to be taken into account;
III. Integrated approaches are essential for supporting the sustainable management of water resources.

In order of supporting the sustainable management of water resources adopting an integrate approach, several paradigms of sustainable resource management have been pursued in the last few decades (e.g. IWRM, AWM, WEFN, …).
In the following the main paradigms and interpretative schemes for sustainable water management are described in detail.

1.2. Sustainable water management paradigms

Following the definition provided by Pahl-Wostl et al. (2011) *“management is the planned and purposeful act or practice of exerting influence on a system and steering it in a certain direction”*.

The same author defines the concept of management paradigm as follows: “*A management paradigm refers to a set of basic assumptions about the nature of the system to be managed, the goals of managing the system and the ways in which these goals can be achieved. The paradigm is shared by an epistemic community of actors involved in the generation and use of relevant knowledge. The paradigm is manifested in artefacts such as technical infrastructure, planning approaches, regulations, engineering practices, models etc*.”

Historically, the dominant paradigm for water management has been based on a traditional "command and control" approach, in which water management resources were dealt with technical solutions. Specifically, this kind of approach is based on the principle that the overall results and consequences of our actions and the possibility of reversibility of the trajectories of change within natural systems can be anticipated. The core of this approach is the control, which is exerted centrally, adhering to rigid and detailed plans for the fulfilment of established goals (Pahl-Wostl *et al.*, 2011). Following the command and control point of view, management interventions can be optimised and their impact can be fully calculated through a disaggregation of the system to be managed into individual elements, neglecting uncertainties, which are dealt with by the establishment of norms. Although such measures are effective for a roughly stable system characterized by a non-linearity, they fall in dealing with the types of non-linear change and unexpected system behaviour typical of the many river basins (Pahl-Wostl *et al.*, 2011). Due to the large number of failures experimented by the above defined approaches, the traditional sectoral and fragmented approach to water management needs to be replaced by other knowledge-based approaches and the holistic management of complex systems (Pahl-Wostl *et al.*, 2011). Therefore, due to the need of dealing with a growing numbers of challenges facing modern society, the paradigm of Integrate Water Resource Management (IWRM), Adaptive Water Management (AWM) and the more recently Water-Energy-Food Nexus (WEFN) have been developed..

1.2.1. Integrated Water Resource Management (IWRM) Paradigm

Integrated Water Resource Management (IWRM) is one of the dominant paradigms of water management since the Earth summit in 1992, during which the paradigm was defined as an innovative integrated approach capable to support water management balancing three different dimensions of sustainable development (economic efficiency, social equity and environmental sustainability) (Gallego-Ayala, 2013).

Nonetheless, the origins of the concept can be found long time before and, accordingly, the literature suggests different dates for the beginning of IWRM.

As per Grigg, (2008) the origins of the IWRM are similar to those of related terms such as "integrated planning" or "integrated environmental management" expressed with the preparation of the USA Flood Controls Act in 1917. Whereas, Jeffrey and Gearey (2006) found the beginning of IWRM with the establishment of the Tennessee Valley Authority in 1933. However, the official date of the IWRM beginning was at Mar del Plata conference in 1977 (Biswas, 2004), after which the IWRM approach gained further international relevance with the 1992 Rio de Janeiro Summit and the Dublin Conference.

One of the most common and widely accepted definition of IWRM is provided by the Global Water Partnership (GWP, 2000), according to which IWRM is:

"..a process which 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".

Nevertheless, according with Grigg, (2008) this definition, appears un-implementable since it does not provide any real guidance to the water professionals as to how the concept can be used to make the existing water planning, management, and decision-making processes increasingly rational, efficient and equitable.

The main innovation of this paradigm is described by Al Radif (1999) defying IWRM as a paradigm promoting integrations among subsectors and fragmented policies within a national economic framework, adopting the demand-driven approach where indigenous and new technologies are used in water allocation and conservation of fresh water supplies. As per Savenije and Van der Zaag (2008) the paradigm allows reconciling basic human needs, ensuring access and equity, with economic development and the imperative of ecological integrity, while respecting transboundary commitments. They identify four dimension of IWRM related to i) the natural dimension, taking the entire hydrological cycle into account; ii) the human dimension, all economic interests and stakeholders; iii) the spatial scale and iv) the temporal scale. According with Borchardt, Ibisch and Bogardi (2016), the IWRM principles includes three essential elements related to (i) the integration of different sectors and different uses and users of water, (ii) the balancing of three pillars economic, social and environmental sustainability and (iii) the participation of stakeholders in decision-making and the strengthening of the role of women. The same authors pointed out that IWRM clearly takes into account the importance of governance and management systems as well as water infrastructures and technological approaches.

In a more holistically sense the paradigm is directly related to concept of ecosystem services, which is defined as per Jewitt (2002) 'the capacity of natural processes and components of natural or semi-natural systems *to provide services and goods that satisfy human needs (directly or indirectly)"*. Ecosystems are highly variable, dynamic and self-organising systems and, thus, IWRM approaches involve dealing with uncertainty (Jewitt, 2002). In IWRM perspective ecosystem is perceived as an important users that need water for their maintenance (Al Radif, 1999). Whereas, water management is perceived as on optimization process of water and related resources and it is configured as an ecosystem approach, which has a hierarchical context that views smaller ecosystems as nested within increasingly larger ecosystems and that defines the boundaries and scales of ecosystems which should change and evolve in response to both human and natural events (Jewitt, 2002). In this framework, sustainable management of water resources is meant as the ability of ecosystem to provide good and services for humanity need on long period maintaining its functionality.

However, despite its ambitious principles, the application of the IWRM in the real life is more controversial. The most critical voices raise serious concerns about the potential implementation of IWRM in real life (Biswas, 2004; Garcia, 2008). The main concern is the lack of evidence of successful implementation of IWRM (Biswas, 2004; Chikozho, 2008; Medema et al., 2008), which remains almost only a theoretical concept. The main problems behind implementing IWRM are both theoretical and practical. Regarding the theoretical issues, a major aspect relates to the deficiencies in IWRM conceptualisation. Whereas, at the practical level, barriers for IWRM implementation include insufficient human resources in water resources institutions (Swatuk, 2005; Gallego-Ayala & Juizo, 2011) and institutional barriers. Moreover, as per Pahl-Wostl (2007) IWRM pay little attention to the interaction with stakeholders during model development and include decision makers and water management authorities as potential ‘‘end users’’ at the end of the process of tool development. A similar concept is expressed by Sivapalan et al. (2012) stating that the main limitations IWRM are related to the examination of single system components in isolation making insufficient to capture the more informative coevolving coupled dynamics and interactions over long periods.

1.2.2. Adaptive Water Management (AWM) Paradigm

Even though the Adaptive Management (AM) concept is in many different theoretical and applied fields, its appearance in the field of natural resource management is attributed to the International Institute for the Analysis of Applied Systems of Vienna since 70s of the last century (Holling, 1978). Following the definition provided by Pahl-Wostl (2007) AM is a systematic process for continually improving management policies and practices by learning from the outcomes of implemented management strategies. The AWM paradigm is based on the concept of socio-ecological system, which is viewed as integrated complex adaptive system where social and ecological subsystems are coupled and interdependent, each other, expressed in a series of mutual feedback relationships (Berkes, 2017). Berkes (2017) argued that the links between the social and the ecological subsystem may include knowledge, such as local knowledge held by resource-based communities, or scientific knowledge held and used by government resource managers. Therefore, the paradigm is directly related to the concept of social learning (Varady *et al.*, 2016), which is become quite a popular term in the literature on natural resource management mainly used to refer to all kinds of processes of learning and change. Several interpretations of this concept exist in literature. Originally, it referred to learning of individuals in a social environment by observation and imitation of others (Bandura, 1977) focussing only on the cognitive processes of individual and neglecting group processes such as development of sheared meaning and values capable to provide a base for joint action.

Folke et al. (2005) refer to social learning (i.e., learning for eco-system management) as a social process capable to produce *social capital and social memory.* Where*, social capital* is defined by the same authors as the glue for collaboration and cooperation capable to produce *social memory* essential for linking past experiences with present and future policies in order to face management issues. Pahl-wostl et al. (2007), provided a more comprehensive definition of the *social learning* derived by the HarmoniCOP (2015) project. Particularly, this project developed a new conceptual framework in order to capture the essential process of multilevel social learning in river basin management focused on the social entity as a whole. This type of learning is characterized by a conceptual framework constituted by multiparty processes influenced by the context in which they are embedded and leading to specific outcomes that may lead to changes in the context and thus to a cyclic and iterative process of change. The context of *social learning* includes governance structure and the natural environment in a river basin. In this view, the AWM is perceived as a learning process described by Pahl-wostl et al. (2007) occurring at different times scale:

1) On short to medium time scales at the level of processes between collaborating stakeholders in collaboration process.
2) On medium to long scales at the level of change in actors network.

3) On long term time scales at the level of change in governance structure.

These three levels correspond to three levels of agent interaction related respectively to micro, meso and macro level. Similar to these three different scales the process may have different levels of intensity and scope described by the triple learning loop theory. Going in further detail, single-loop learning refers to a refinement of actions to improve performance without changing guiding assumptions and calling into question-established routines. Incremental changes in established practice and action aim at improving the achievement of goals. This phase might also include a first improvement of the capacity to make and implement collective decisions.

Double-loop learning refers to a change in the frame of reference and the calling into question of guiding assumptions. Where, reframing implies a reflection on goals and problem framing (priorities, include new aspects, change boundaries of system analysis) and assumptions how goals can be achieved. Actors explore the full space of reframing within structural constraints. This might lead to changes in the actor network characterizing the resource governance regime. Improvement is achieved by experimenting with innovative approaches and new kinds of measures.

Triple-loop learning refers to a transformation of the structural context and factors that determine the frame of reference. This kind of societal learning refers to transitions of the whole regime. (e.g. change in regulatory frameworks, practices in risk management, dominant value structure). In opposition to the social learning as a process of social change, Reed *et al.* (2010) pointed out the need of distinguish social learning as a concept from the conditions or methods that may facilitate social learning, e.g., stakeholder participation, and the potential outcomes of social learning processes, e. g., environmental behaviour. They suggested that if learning is to be considered “social learning,” it must: i) demonstrate that a change in understanding has taken place in the individuals involved; ii) go beyond the individual to become situated within wider social units or communities of practice within society. Despite the different interpretations of the social learning concept, several authors argued the capability of social learning process to support sustainable management of water resource (Pelling and High, 2005; Tschakert and Dietrich, 2010; Varady *et al.*, 2016). Particularly in these works, the concept of sustainability is directly related to the concept of resilience and, accordingly, the sustainable management of water resources is targeted to flexible solutions rather than optimal solution, exploiting the capabilities of the socio-environmental system its resilience to possible shocks of different origins.

Like the IWRM paradigm, also the AWM is a more controversial paradigm in scientific field, due to its inapplicability to the real life. For example Brugnach and Ingram (2012) argued that despite the great advances in promoting participatory and inclusive practices, the two paradigms still contain antiquated decision-making paradigms, in which the ‘natural system’ is seen as external to human. They emphasised on the relational concept of knowledge, highlighting the importance of the coproduction of knowledge for participatory practices. Following their point of view, participatory solutions require a reformulation of decision-making models that need to take into account those who make the decisions and the processes by which decisions are agreed upon, as well as their influence upon eco-system functioning.

1.2.3. Water Energy Food Nexus (WEFN) Paradigm

The Water-Energy-Food Nexus (WEFN) was introduced by Hoff (2011) in response to climate change and social impacts (i.e., population growth, globalization, economic growth, and urbanization). Since then, WEFN has shown to be an approach capable to integrate management and governance across sectors and scales, thus supporting the transition process towards sustainability. Indeed, sectoral approaches of policy-making (i.e., command and control approaches), has led to policy responses with inadequate attention to the complex interactions that exist between sectors and resource systems, resulting in policies creating unintended consequences (Leck *et al.*, 2015).

The main innovation of such paradigm is related to the fact that nexus perspective moves the focus from water to its interaction with other two resources (Giupponi, Gain and D’Odorico, 2015). Although IWRM seeks to involve all sectors from a water management perspective, the WEFN approach considers the three issues water, energy and food equally important. Consequently, the IWRM paradigm considers water as its point of departure, whereas the nexus ideally looks holistically at WEFN or as a system from the outset (Leck *et al.*, 2015).

Different perspectives of the WEFN exist depending on the short, middle and long term goals of the region and of the sector, and the perspective adopted will affect the policy design (Bazilian *et al.*, 2011). The water perspective considers food and energy systems are users of the resource: for example, in case of the water reuse, in which energy is required to produce water for food; on the other hand, in a food perspective, energy and water can be considered as inputs, as in the case of irrigated crops, which need water for increasing yield and where energy is essential for pumping. At the end, from the energy perspective, water as well as bio-resources (e.g., biomass) are an input or a resource requirement and food is the output.

Nevertheless, as discussed by FAO (2014), the nexus perspective allows to analyse the complex linkages among resources and their usage, that need to be captured to avoid shifting problems from one sector to another. It highlights the importance in the nexus assessment of involving a participatory process helping policy-makers to understand critical situations, where resources are under pressure, and which tipping points exist in terms of possible interventions. Going in further details, a general stepwise approach for WEFN assessment and characterization was proposed by FAO (2014), according to which two distinct phases characterizing the WEFN assessment can be identified:

- Assessment of the context nexus status that allows to understand societal priorities and different and competing local environmental, economic and social goals. This can be achieved in a qualitative manner through experts' opinion or multi-stakeholder consultation. Nevertheless it needs to be strengthened on a quantitative assessment of resources exploitation. In doing so a set of sustainability indicators is surely helpful. Section 1.3 summarizes the main sustainability indicators.
- Quantitative assessment of the plausible effects on the natural environment and the society due to potential interventions or to the adoption of new policies. This

> requires that specific interventions and their related impacts need to be identified and discussed with local community. The need to assess interventions against context status is an essential task to better analyse the appropriateness of different interventions according to the context where they are implemented.

Although several approaches were developed in the WEFN framework (Siddiqi and Anadon, 2011; Hardy, Garrido and Juana, 2012; Rasul, 2014; Dale *et al.*, 2015; Keskinen *et al.*, 2015), only few of them are focussed at the local scale (e.g., Granit *et al.*, 2012; Lawford *et al.*, 2013). Therefore, the literature analysis reveal that an urgent need of operationalizing the above approaches at local scale, which is the most policy relevant scale, exists (M Brugnach and Ingram, 2012; M. Brugnach, Craps and Dewulf, 2014).

1.3. Sustainability indicators for WEFN characterization

The knowledge of the current state of water resources, the evaluation of system's dynamics, and the plausible consequences on the system induced by any interventions, is the basis of a correct decision-making process. In this framework, indicators can provide a basic guide for the decision process in several ways starting by the early warning of divergences from sustainable trajectories in time to avoid economic, social and environmental damages. The key role of sustainability indicators is to provide a measuring tool, monitoring and reporting on progress towards sustainability. With this aim, a growing numbers of indicators are recently introduced in the technical literature.

OECD (1996) provides an useful guide for environmental sustainability indicators related to the agricultural production. According to this, the general criteria, which sustainability indicators need to meet, are:

- policy-relevant – they should address the key environmental issues faced by governments and other stakeholders in the agriculture sector;
- analytically sound – based on sound science, but recognising that their development involves successive stages of improvement;
- measurable – feasible in terms of present or planned data availability and cost effective in terms of data collection;
- easy to interpret – the indicators should communicate essential information to policy makers and the wider public in a way that is unambiguous and easy to understand.

Among the different indicators developed in scientific field, they can be classified in four categories as follows:

- *Indicators describing the agriculture in the broader economic, social, and environmental context*. Among the most relevant can be mentioned for example the A*griculture GDP* (i.e., the share of agriculture in total Gross Domestic Product); *Farm employment* (i.e., share of agriculture in total civilian employment); *Farmer age/gender distribution* (i.e., share of new farmers entering agriculture by age and gender categories); *Farmer education* (i.e., educational level of farmers). Another import indicators belonged to this category are the *farm income* and the *economic land productivity* describing the economic value derived per unit of produced crop.

- *Indicators describing farm management and the environment.* For example, the *Organic farming* is an important indicator referring to the share of farms or the total agricultural area having a certified organic farming system or in the process of conversion to such a system. The nutrient management, that is the share of farms or cultivated area with nutrient management plans, assumes similar importance.
- *Indicators describing use of farm inputs and natural resources* such as for example *Water use efficiency* divided in *Water use technical efficiency and* Water *use economic efficiency.* The former indicates, for selected irrigated crops, the yield (tonnes) per unit volume of used irrigation water, whereas, the *Water use economic efficiency* refers to all the irrigated crops, the monetary value of agricultural production per unit volume of used irrigation water. Another important indicator belonging to this category is the *Water stress index, whose more common definition is due to* Falkenmark et al., (1989), that identifies a water scarcity condition when the per capita availability of water resources is lower than 1000 m^3/year. Similarly, Vörösmarty et al. (2005) defined the water stress condition when the ratio of demand for fresh water per year to availability is greater than 0.4.
- *Indicators describing environmental impacts of agriculture.* In this category are the water quality indicators such as *Water quality risk index* describing potential concentration of nitrate (or phosphorus) in the water flowing from a given agricultural area; *Water quality state Index* referring to the nitrate (or phosphorus) concentration in water in vulnerable agricultural areas: the percentage of surface water and groundwater above a national threshold value of nitrate concentration (NO_3 mg/l) or phosphorus (P_{total} mg/l). To this category belongs the

greenhouse gas emission that expresses the agricultural emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in CO_2 equivalent terms.

Related to the last category, recently some indicators have been introduced; among them, it is worth to mention the V*irtual Water Content* defined by Allan (2003) that is the amount of water embedded in a specific product. An its extension is the *Water Footprint Index* defined by Hoekstra *et al.*, (2011) that is a comprehensive indicator of freshwater resources appropriation, because it estimates the volume of freshwater used for producing the good over the full supply chain. More in detail, three different component characterize this index, that are related to i) green water component referring to the consumption of rainwater stored into soil as soil moisture, ii) the blue water component referring to the consumption of surface water and groundwater, and iii) the grey one that refers to the volume of freshwater that is required to assimilate the load of pollutants, being known the natural background concentrations and existing water quality standards. According to Hoekstra *et al.*, (2011), the water footprint differs from other water use indicator because it is related on the consumptive use. Therefore, it does not include blue water use insofar as this amount of water is returned to where it came from. Considering the agricultural production, a large number of studies focused on water resource impacts due to the agricultural production by means of the water footprint concept (e.g. Hoekstra and Mekonnen, 2008; Chapagain and Orr, 2009; Ercin et al., 2013; Donoso et al., 2015; Chukalla et al., 2015; Mekonnen et al., 2015) Chouchane *et al.*, 2015a)

Starting from its original definition, that was referred only to water, the footprint approach has been extended to the *carbon and the land issues* and different studies provided an integration of these indicators (e.g. Casolani et al., 2016; Daccache et al., 2014; Ibidhi et al., 2017) in order to evaluate the wider environmental impacts of the agricultural practices. For example, Chouchane *et al.*, (2015) proposed an integration of the *water footprint index* taking into account also the *economic water productivity and the land productivity, where* this last is related to the economic value derived per unit of water used, i.e. dollars per drop.

A similar approach was adopted by Rulli et al. (2016) in which the WEFN is operationalised considering the water footprint and land footprint of biofuel production. Other different studies try to operationalize the nexus proposing composite indexes. Among them, Moioli et al. (2016) introduced the Nexus index, a synthetic indicator capable to describe the complex inter-relationship between energy and food production focussing on the water use for biofuel crops cultivation. Mainly focusing on the socio-economic security at national and international scale, Willis et al. (2016) introduced the Food-Energy- Water Security Index (or FEW Index) which is a mix of three sub-indices related to food, energy, and water security; it includes many dimensions, including availability and accessibility of food, water and energy.

CHAPTER 2

ASSESSING THE SUSTAINABLE MANAGEMENT OF WATER RESOURCES FOR IRRIGATION PRACTICES

"We shape our buildings; thereafter our buildings shape us"

Winston Churchill

This study aims to provide an operational methodology, operating within WEFN paradigm, in order to support decision-makers in their strategic choices related to sustainable management of water resources at locale scale. As described in chapter 1, a sustainable management of water resources needs the adoption of an integrated holistic approach, by:

i) Analysing the intertwined linkages among resource exploitation
ii) Integrating management and governance across sectors and scales.

In this context, inter-disciplinary research focussed on the WEFN paradigm (physical, agro ecological, social sciences, economics) is crucial for supporting sustainable management of water resources (Scanlon *et al.*, 2017), since it aids in linking different fields (e.g., energy and water) and in recognizing the importance of preserving ecosystem integrity and its link with local people's well-being. Due to the lack of a recognized WEFN approach operating at local scale, this study proposes a local scale methodology capable to evaluate the multi-dimensional implications of irrigation water use by identifying the main factors controlling the selection and exploitation of water. Specifically, the complexity charactering the dynamic of the irrigation water management system is analysed developing a conceptual model in which the relationships among the main involved actors are analysed in order to understand how actor's behaviour could affect system' dynamics. The analysis of the system' dynamics allow also to identify the main factors conditioning a sustainable management of water resources and a set of indicators of sustainability has been defined in order to evaluate in a quantitative way the state of the system. It is worth to mention that the integration of the above defined approaches is essential in supporting the choices regarding the effects of a given policy.

2.1 *Understanding system's dynamics*

The aim of this approach is in defining the problem in a given area allowing to identify its dynamic and the main factors conditioning water resources sustainability, whereas the expected outputs are:

- Socio-Ecological boundaries of the system definition;
- Identifications of the main stakeholders interesting in the sustainable management of water resources and elicitation of their mental model;
- Conceptual model of the system's dynamics.

In a more general sense, a *system* is defined as a collection of elements that continually interacts over time to create an unified whole, in which the underlying pattern of interactions between the elements of the system defines the *system's structure* (Simonovic, 2011). Referring to the irrigation water management system, the main elements constituting the system are related to decisional actors that continuously interact each other over time. Therefore, a dense network of relationships among different stakeholders involved within the system, spanning among and across ecological, economic and socio-political domains, constitutes the system structure (Giordano, Brugnach and Pluchinotta, 2016).

For implementing the aforementioned purpose, two different phases characterize the methodology, each of which is briefly summarized as follows:

1. Stakeholder analysis allowing at identify the main actors involved in the process of irrigated water management by defining the environmental and social bounders of the system;
2. Elicitation of decisional-actor's mental model to analyse the behaviour of each actor before selected by defining their objective and interests and conceptual model development of the system's dynamic by evaluating the relationship among stakeholders involved in decisional process.

2.1.1 Stakeholder analysis

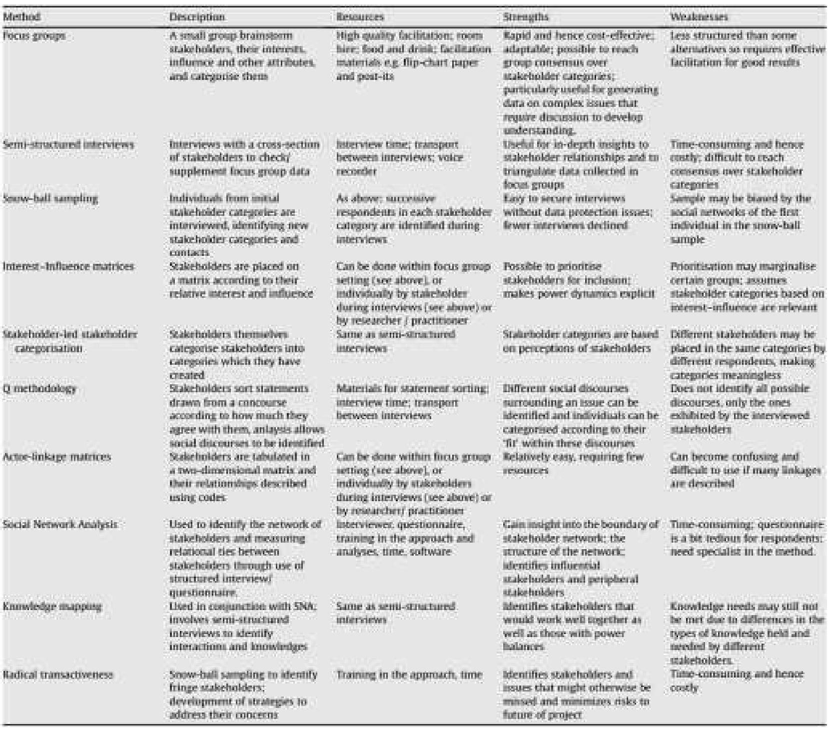
Following the definition provided by Reed *et al.* (2009), stakeholder analysis is a process aiming to:

I. Define aspects of a social and natural phenomenon affected by a decision or an action;
II. Identify individuals, groups and organisations who are affected by or can affect those parts of the phenomenon (this may include non-human and non-living entities and future generations);
III. Prioritise these individuals and groups for involvement in the decision-making process.

Therefore, the first essential step of the stakeholder analysis is answering the question: who is a stakeholder?

The term "stakeholder" was introduced in the last 1708, by indicating a person entrusted with the stakes of bettors or, more in general, a bet or a deposit (Stanghellini, 2010). Nonetheless, a dominant meaning is in business and management literature, in which the term stakeholder refers to one who has a share or an interest in an enterprise. The most recognized definition is by Freeman & Mcvea (2001), which defined stakeholder: "any group or individual who can affect or is affected by the achievement of the organization's objectives". This definition has prevailed in the public and non-profit management literature since then. Among all, this study will refer to the definition proposed by the European Commission (European Comission, 2003), proposed during the implementation of the Water Framework Directive, which is the most versatile and widely accepted in scientific field due to its large degree of inclusivity. Particularly, it states, "a stakeholder can be any relevant person, group or organisation with an interest in the issue, either because they will be affected by the subject (victim, gainer) or because they have influence, knowledge or experience with the subject". According with Stanghellini (2010), this definition has its crucial element in the role played by the knowledge and the experience as means to affect something or simply to have a connection with something. Starting from such a definition, the goal is in identifying the main actors involved in a water management system, evaluating their interest and objectives in order to analyse their behaviour within the system. Nonetheless, before stakeholder identification, the essential element is defining the boundaries of the social and ecological phenomenon, for a better characterization of the focus. If the boundaries of the phenomenon itself are clearly defined, then stakeholders can be easily identified. Indeed, according with Reed *et al.* (2009), who is included and who is omitted depends on the assigned boundary of the system. Usually, identifying the stakeholders is an iterative process, during which additional stakeholders are added as the process continues, mainly using expert opinion, focus groups, semi-structured interviews, snowball sampling, or a combination of these (Reed *et al.*, 2009).

Figure 2, (Reed *et al.,* 2009) summarizes the methods, including details of the required resources, level of stakeholder participation, and their strengths and weaknesses.



Method	Description	Resources	Strengths	Weaknesses
Focus groups	A small group brainstorm stakeholders, their interests, influence and other attributes, and categorise them	High quality facilitation; room hire; food and drink; facilitation materials e.g. flip-chart paper and post-its	Rapid and hence cost-effective; adaptable; possible to reach group consensus over stakeholder categories; particularly useful for generating data on complex issues that require discussion to develop understanding.	Less structured than some alternatives so requires effective facilitation for good results
Semi-structured interviews	Interviews with a cross-section of stakeholders to check/ supplement focus group data	Interview time; transport between interviews; voice recorder	Useful for in-depth insights to stakeholder relationships and to triangulate data collected in focus groups	Time-consuming and hence costly; difficult to reach consensus over stakeholder categories
Snow-ball sampling	Individuals from initial stakeholder categories are interviewed, identifying new stakeholder categories and contacts	As above; successive respondents in each stakeholder category are identified during interviews	Easy to secure interviews without data protection issues; fewer interviews declined	Sample may be biased by the social networks of the first individual in the snow-ball sample
Interest–Influence matrices	Stakeholders are placed on a matrix according to their relative interest and influence	Can be done within focus group setting (see above), or individually by stakeholder during interviews (see above) or by researcher / practitioner	Possible to prioritise stakeholders for inclusion; makes power dynamics explicit	Prioritisation may marginalise certain groups; assumes stakeholder categories based on interest–influence are relevant
Stakeholder-led stakeholder categorisation	Stakeholders themselves categorise stakeholders into categories which they have created	Same as semi-structured interviews	Stakeholder categories are based on perceptions of stakeholders	Different stakeholders may be placed in the same categories by different respondents, making categories meaningless
Q methodology	Stakeholders sort statements drawn from a concourse according to how much they agree with them, anlaysis allows social discourses to be identified	Materials for statement sorting; interview time; transport between interviews	Different social discourses surrounding an issue can be identified and individuals can be categorised according to their 'fit' within these discourses	Does not identify all possible discourses, only the ones exhibited by the interviewed stakeholders
Actor-linkage matrices	Stakeholders are tabulated in a two-dimensional matrix and their relationships described using codes	Can be done within focus group setting (see above), or individually by stakeholders during interviews (see above) or by researcher/ practitioner	Relatively easy, requiring few resources	Can become confusing and difficult to use if many linkages are described
Social Network Analysis	Used to identify the network of stakeholders and measuring relational ties between stakeholders through use of structured interview/ questionnaire.	Interviewer, questionnaire, training in the approach and analyses, time, software	Gain insight into the boundary of stakeholder network; the structure of the network; identifies influential stakeholders and peripheral stakeholders	Time-consuming; questionnaire is a bit tedious for respondents; need specialist in the method.
Knowledge mapping	Used in conjunction with SNA; involves semi-structured interviews to identify interactions and knowledges	Same as semi-structured interviews	Identifies stakeholders that would work well together as well as those with power balances	Knowledge needs may still not be met due to differences in the types of knowledge held and needed by different stakeholders.
Radical transactiveness	Snow-ball sampling to identify fringe stakeholders; development of strategies to address their concerns	Training in the approach, time	Identifies stakeholders and issues that might otherwise be missed and minimizes risks to future of project	Time-consuming and hence costly

Figure 2: Stakeholders analysis approaches (Reed *et al.*, 2009)

2.1.2 Elicitation of stakeholder mental model of the system's dynamic

The elicitation of stakeholder's mental model aims at studying the different actor's behaviour in order to capture and analyse the system's dynamic. Its main outcomes are:

- Stakeholder's mental model;
- Conceptual model developing to describe the system's dynamic;
- Identifications of the main elements influencing sustainable management of water resource.

The core is related to the mental model concept definition; about it several definition can be found in the scientific literature (Doyle and Ford, 1998). This work refers to Sterman (2000) definition, which stresses the implicit "*beliefs about the network of causes and effects that describe how a system operates, the boundary of the model (the exogenous variables) and the time horizon we consider relevant e our framing or articulation of a problem*". Therefore, a mental model is built of causal knowledge about how a system works and evolve in time (Sterman, 2000) and is capable of representing the perceived cause-effect chains influencing the dynamic evolution of a system (Jones *et al.*, 2011).

Due to the ability of system dynamic (SD) approach to study complex feedbacks driven systems in which non-linearity usually plays a key role (Davies and Simonovic, 2010; Jeong and Adamowski, 2016), mental models based on SD have been implemented in this work. According to Sterman (2000), feedback is one of the core concepts of SD theory and a Causal Loop Diagram (CLD) is usually used to catch the feedbacks of the system at the first step of modelling. The main assumption in developing a CLD is that the systems can be represented as a collection of variables in which the interaction between them defines the system dynamics (Voinov and Bousquet, 2010). A CLD is made up of variables connected by arrows denoting the causal influence among them. The arrows are marked by a polarity (+ or −), suggesting the type of effect that an element can have on the other (Sterman, 2000). A positive or negative polarity shows whether the variables move on the same or opposite direction (Sterman, 2000). The arrows are drawn in a circular manner indicating the cause and effect leading to a feedback loop which is a closed sequence of cause and effects. The feedback loops may occur in either a reinforcing (R) or balancing (B) loop type. Reinforcing loops representing growing or declining actions, whereas balancing are self-correcting mechanism that counteract and oppose a change.

Once the stakeholder mental models are defined, overlapping them allows at characterizing and describing the system dynamic. While the analysis of the main loops activated within the system due to stakeholder's behaviour allows to identify the main elements affecting sustainable management of water resource.

2.2 Sustainability assessment of irrigation water use in the WEFN framework

The rationale behind the index-based approach is the strict connection, in the WEFN perspective, between water management issues and sustainability principles. For this aim, three elements need to be jointly taken into account: environment, people and economics (Avellàn et al. 2017), since increasing pressures on environmental resources may undermine the ecosystems' resilience, hamper the economic growth, and limit the human well-being. The WEFN approach proves to capture the integrated nature of irrigation practices, which has a crucial role on food production (Avellàn et al. 2017). Starting from this, the proposed index-based methodology assesses the key elements that characterize irrigation practices and related water resources exploitation. More in detail, water and energy consumption are considered the main determinants of crop production and water source selection, along with the economic benefit of each crop production. Three different indices are accordingly introduced and briefly summarized in the following pages, while the full details are provided in specific subsections (see 2.1, 2.2, 2.3 subsections).

- The *Irrigation Water Footprint Index* is a non-dimensional index assessing the impacts of irrigation practices for the production of a specific crop using the renewable water resources.
- The *Energy Footprint for Irrigation Index* is used to compare the energy required for pumping and for supplying water from-source-to-field and the unit revenue coming from the production of a given crop.
- The *Irrigation Water-Cost Footprint Index* is a non-dimensional index for comparing the cost of irrigation water and the unit revenue associated to the production of a given crop.

The three indices can be either directly applied to single crops or to complex cropping patterns in mixed irrigation districts by weighting each crop area on the entire domain. Moreover, each index can be either computed in aggregated form or by referring to a specific water source (e.g., surface or ground water). Consequently, the differences in the estimation of the unit water costs for on-farm groundwater supply, and the specific water pricing schemes for common irrigation networks can be considered (e.g., volume-based versus surface-based water tariffs). Moreover, specific regulations and management conditions (i.e., water and pumping efficiencies), which may be relevant to a given geographical area, can be explicitly included.

It is worth noting that the main aim of the proposed approach, in its current form, is not to provide an general sustainability assessment based on comparing of the values of the indices with thresholds or benchmarks; the methodology mainly aims to provide a relative sustainability assessment, focused on the comparative analysis of the values of indices over a defined area. This approach would allow the final user to easily estimate the key parameters of an irrigation practices (e.g., cropping pattern, water source, water pricing, etc.) and to define those more sustainable, being known the site's peculiarities. Although the methodology was created to operate at the local scale, it could be also used on wider one, even if in such case the required data and the computational burden could significantly increase.

A detailed description of the key characteristics for the proposed set of indices is presented in the following (see subsections 2.2.1, 2.2.2, 2.2.3 respectively).

2.2.1 Irrigation water footprint Index

The definition of index $I_{w,i}$ is based on the *Water Footprint* (*WF*) concept by Hoekstra (2003), concerning the consumptive water use of a given agricultural production. Referring to the *WF* definitions, two different components are considered, namely: i) the green water footprint (WF_{green}) that is the crop water consumption due to the rainwater stored as soil moisture; and ii) the blue water footprint (WF_{blue}) that is i.e. the crop water consumption by surface and ground water (Hoekstra *et al.*, 2011).

The index expression for a fixed crop *i* is given in Eq. (1) as the ratio between the blue water footprint ($WF_{blue,i}$) and the effective annual precipitation. The latter is defined as the difference between the annual precipitation volume over the area of the *i-th* crop (P_i) and the green water footprint ($WF_{green,i}$).

$$I_{w,i}\,[-] = WF_{blue,i}/(P_i - WF_{green,i}) \qquad (1)$$

where, P_i is computed as the product between the total annual precipitation measured (in mm) at the rain gauge and the total area cultivated of a given crop S_i (in ha).

As proposed by Hoekstra et al. (2011), the $WF_{blue,i}$ and $WF_{green,i}$ can be calculated by multiplying the net crop water requirements ($CWU_{blue,i}$ and $CWU_{green,i}$) by S_i, as in Eq.s (2) and (3).

$$WF_{blue,i}\,[m^3] = CWU_{blue,i} \times S_i = ET_{blue,i} \times 10 \times S_i, \qquad (2)$$

$$WF_{green,i}\,[m^3] = CWU_{green,i} \times S_i = ET_{green,i} \times 10 \times S_i, (3)$$

where both $CWU_{blue,i}$ and $CWU_{green,i}$ are expressed in m^3/ha and directly calculated from the blue and green evapotranspiration components ($ET_{blue,i}$ and $ET_{green,i}$) over the entire irrigation season, using the CropWat® software (Clarke, Smith and El-Askari, 2000). Further details on the calculation of $ET_{blue,i}$ and $ET_{green,i}$ are provided in Appendix B.

Although several studies are based on an WF, few explicitly refer to groundwater sources (Vanham, 2015). For this reason, to better highlight the differences between the surface and ground water sources, the irrigation water footprint index has been evaluated separately in the two cases. Two components, $I_{w(s)}$ (Eq. (4)) and $I_{w(g)}$ (Eq. (5)), can be thus computed as follows:

$$I_{w\,(s),i}[-] = SWF_{blue,i}/(P_i - WF_{green,i}) \; (4)$$

$$I_{w\,(g),i}[-] = GWF_{blue,i}/(P_i - WF_{green,i}) \; (5)$$

The assessment of surface and ground water footprint blue ($SWF_{blue,i}$ and $GWF_{blue,i}$) is performed according to the Eq.s (6) and (7). Specifically, the $SWF_{blue,i}$ is computed by multiplying the volume of the surface water extracted for crop *i* ($S_{w,i}$) and the related water efficiency ($e_{s,i}$), calculated according to the "chain of efficiency" (Hsiao et al., 2007). Instead, the groundwater component $GWF_{blue,i}$ can be evaluated as the difference between the total blue-water footprint and its surface component.

$$SWF_{blue,i}[m^3] = S_{w,i} \times e_{s,i}; \qquad (6)$$

$$GWF_{blue,i}[m^3] = WF_{blue,i} - SWF_{blue,i} \ (7)$$

Efficiency $e_{s,i,}$ has crucial importance in relating the water consumption to the withdrawals due to environmental, engineering, management, social and economic constraints (Hsiao et al. 2007). Focusing on water sources, infrastructural performance, and specific irrigation management criteria, $e_{s,i}$ is typically calculated as the product of the following components:

- *Conveyance efficiency (e_c),* the efficiency of the irrigation network, conditioning the amount of water lost during the delivery process. Although a single term is used, it encompasses multiple concepts, namely evaporation losses from channels and storages, outflows, seepage/leakage, system filling, irrigation metering inaccuracy, unrecorded uses (Marsden Jacob Associates, 2003). Its value may range from very low to very high values (0.50- 0.96) according to both physical and operational conditions, whose specific impact on e_c is not totally known;
- *Farm efficiency* (e_{farm}), is the efficiency related to the farm management techniques. Typical values range between 0.40 and 0.95;
- *Application efficiency* (e_{app})*,* is the efficiency related to irrigation methods (i.e., sprinkler or drip irrigation); it varies from 0.30 to 0.95.

The magnitude of e_c is often negligible for farm-scale groundwater withdrawals, due to the reduced extension of conveyance networks.

The S_w volume can be either directly monitored at the source or indirectly estimated using the gross irrigation concept (GI_s in m^3). In both cases, the main causes of inefficiency should be identified and the suitable components included in the computation of the "chain of efficiency". It is worth mentioning that, despite the focus of this study is related to the surface and ground waters, the approach can be easily generalized also to other cases where multiple resources are exploited (e.g., reuse or desalinated water). The data required for the implementation of the index are mainly climatic (i.e. precipitation and temperature). More information are available in Appendix B.

2.2.2 Energy Footprint for Irrigation Index

The energy footprint for the irrigation index ($I_{en,i}$) takes in to account the energy requirement from-source-to-field to obtain a unit revenue for the *i-th* crop. The $I_{en,i}$ strongly depends on a specific water source, as well as on the characteristics (water losses and operational pressures) of the conveyance, distribution and irrigation systems. Therefore, the $I_{en,i}$ is defined according to Eq. 8, as the ratio between the energy required to supply water from a specific water source to the field, at the required water pressure, and the economic land productivity.

$$I_{en,i}\ [kWh/€] = E_{a,i}/E_{lp,i} \quad (8)$$

This index can be computed referring to both surface water ($I_{en(s),i}$) and groundwater ($I_{en(g),i}$) withdrawals, according to Eqs. (9) and (10), respectively:

$$I_{en(s),i}\ [kWh/€] = E_{a(s),i}/E_{lp,i} \qquad (9)$$

$$I_{en(g),i}[kWh/€] = \ E_{a(g),i}/E_{lp,i} \qquad (10)$$

$E_{a(s),i}$ and $E_{a(g),i}$ define the unit energy requirement (in kWh/ha) to irrigate 1 unit area (ha) of the *i-th* crop, whereas the $E_{lp,i}$ is the economic land productivity of the same crop (in €/ha). According to Barutçu et al. (2007) and Daccache et al. (2014), the energy requirements for irrigation mainly depend on the water source (i.e., surface, ground, reclaimed, etc.) and the used irrigation system (i.e., drip irrigation, sprinkler, etc.). Therefore, the two components $E_{a(s),i}$ and $E_{a(g),i}$ are computed as the product between the energy required to pump a unit volume of water from a specific source to the water pressure required on the field (in kWh/m^3) and the gross volume of water abstracted to irrigate an unit area (m^3/ha), assuming a unique source of irrigation. Concerning land productivity, $E_{lp,i}$ represents the economic value of a crop yield per unit area (€/ha) and is calculated as the crop yield (kg/ha) times the crop market value (€/kg). Therefore, the land productivity is a scale factor of the energy footprint for irrigation, since it has a foremost importance in driving farmers' decisions, above all concerning irrigation (Elshafei *et al.*, 2014; Chouchane *et al.*, 2015b). This index is not sensitive to the specific analysis scale, since it is calculated based on unit parameters (e.g., unit crop yield or crop market value), and can be adapted to other water sources (e.g., reclaimed water), simply by assessing the unit energy requirement for irrigation associated to the specific water sources.

Besides to yield and crop market price, the required data for calculating the index are the amount of water withdrawals from a specific water source and the efficiency of the pumping systems. Even in this case, more information are available in Appendix B.

2.2.3 Irrigation Water-Cost Footprint Index

The irrigation water-cost footprint index ($I_{e,i}$) estimates the water cost needed to supply water from a specific source to the field to obtain the unit revenue for the *i-th* crop in terms of economic land productivity. It is well known that farmer's revenue and the water cost influence the farmer's behavior in selecting crops and irrigation water source (Portoghese *et al.*, 2013; Elshafei *et al.*, 2014; Pham and Smith, 2014; Chouchane *et al.*, 2015b; Giordano *et al.*, 2015). This index is expressed as the ratio between the cost for water and the economic land productivity (Eq. (11)), in order to evaluate the incidence of water cost on a farmer's revenue:

$$I_{e,i}[-] = C_{w,i}/E_{lp,i} \quad (11)$$

Due to the differences in water cost components between surface water resources, typically characterized by a centralized management, and individual farm-scale groundwater withdrawals, the formulation is proposed taking into account the two main water sources as shown in Eq.s (12) and (13).

$$I_{e(s),i}[-] = C_{w(s),i}/E_{lp,i}\,, \quad (12)$$

$I_{e(g),i}[-] = C_{w(g),i}/E_{lp,i.}$ (13)

In our case study, the cost of surface water is estimated considering the water tariff applied by the irrigation district authority, whereas the groundwater cost is computed referring only to the variable costs due to energy consumption, neglecting costs due to the maintenance and the depreciation of the equipment . Therefore, in Eq.s (12) and (13), two different water costs ($C_{w(s),i}$ and $C_{w(g),i}$, in €/ha) are calculated for each crop, assuming that the irrigation requirement is fully satisfied using a well-defined source. Referring to the surface water withdrawals, the water tariff defined by the district authority may be a volumetric water tariff (t_w expressed in €/m^3) or a flat rate related to the irrigated area (t_w expressed in €/ha). For a volumetric water tariff, the water cost can be calculated as the product between the irrigation water tariff (in €/m^3) and the amount of water supplied per unit crop area as shown in Eq. (14) (i.e., the gross unit irrigation GUI_i in m^3/ha).

$C_{w(s),i}\,[€/ha] = t_w \times GUI_i$ (14)

Referring to groundwater withdrawals, the water cost $C_{w(g),i}$ (expressed in €/ha) depends on the energy tariff ($t_{e,}$ expressed in €/kWh), unit energy consumption ($E_{w(g)}$ in kWh/m^3), and the GUI_i, as shown in Eq. 15:

$C_{w(g),i}[€/ha] = t_e \times E_{w(g)} \times GUI_i$ (15)

As for the others, the irrigation water-cost footprint can be easily evaluated considering different water sources and scales of analysis.. The index could be further split into additional subcomponents to take into account the use of other water sources, with their specific costs. For further information on the computation of the index, including all equations used, please refer to Appendix D.

CHAPTER 3

IRRIGATION WATER MANAGEMENT IN PUGLIA REGION

> *"Somewhere, something incredible is waiting to be known."*
>
> *Carl Sagan*

3.1 Geomorphological aspects

Puglia region is a semi-arid peninsula in Southern Italy (Figure 3) covering approximately 20,000 km^2 and bordering the Adriatic Sea to the East, the Ionian Sea to the South-East, and the Strait of Òtranto and Gulf of Taranto to the South.

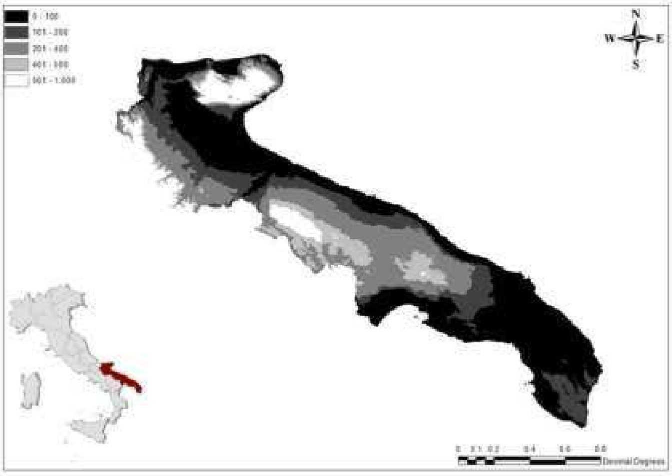


Figure 3: Puglia Digital Elevation Model (DEM)

It is characterized by reliefs of modest entity (Figure 3), around 1% of the region has altitudes of more than 1000 m above sea level, and approximately 45% can be considered a hilly area, while about 54% presents a quite flat area. From a climatic point of view, Puglia has a typical Mediterranean climate, with moderate and quite dry winter, and hot and very dry summer (i.e., raining days range from 60 to 80). Annual rainfall, as shown in Figure 5, varies from 450 mm in Capitanata to about 1000 mm on Gargano region. Due to both adverse climatic conditions and to the karstic characteristics of the soil, limited surface water courses characterizing the region (AdB Puglia, 2004). According to the river basin hydrological management plan (AdB Puglia, 2004), the most relevant rivers are “Ofanto” and the “Fortore” in the Capitanata, the “Lato” and “Galaso” in Taranto area and “Canale Reale” near Brindisi. On the other hand, ground water has a great importance with different characteristics within the region. The main acquifers are located in three distinct zones related to i) the Mesozoic carbonate successions of the foreland, in North-East of the region, forming the Gargano; ii) Murge, in the central area of the peninsula, where the water table moves under pressure at a considerable depth below the sea level, and iii) Salento limestone outcrops in Southern peninsula, where the groundwater flows a few meters above sea level. Groundwater level range from few tens of meters in the coastal zones to and 500 m the inland of the region. In the western part of the region, the water basins are characterized by different flow regimes and geomorphological peculiarities, since they are seasonal watercourses collecting water from bottom karst carvings called gravines. The waters of these streams partly penetrate through the limestone rocks, feeding the water table and, where stratigraphic conditions exist, may emerge as springs. The same type of basin is also associated with the surface hydrography of the Murge, where erosive grooves locally called "lame" are present. Finally, in southern part of the region, the endoreic basins are a typical geomorphological system; the water that flows into them superficially penetrates through infiltration into permeable soils and is delivered to the aquifer through the numerous and diversified epigeous and hypogee karst forms.

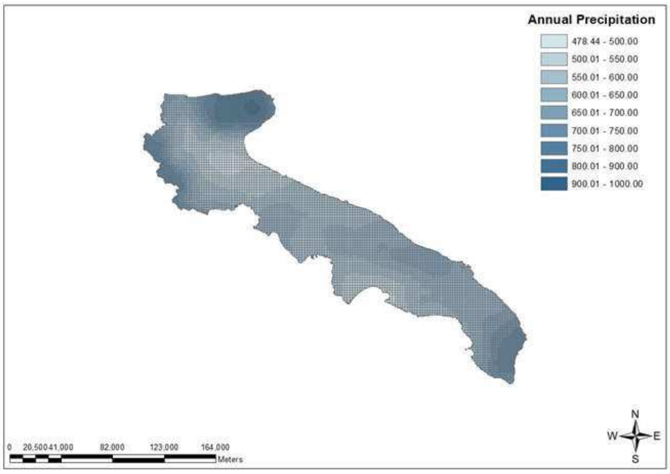


Figure 4: Spatial distribution of average annual precipitation in Puglia region.

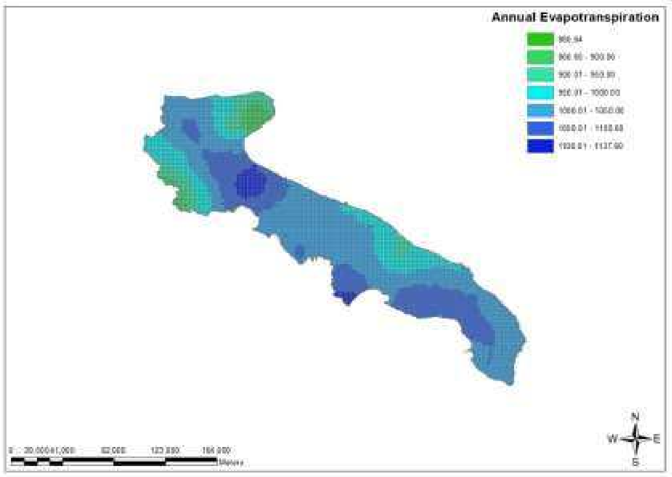


Figure 5: Spatial distribution of average annual evapotranspiration in Puglia region.

3.2 Agricultural production in Puglia

Agricultural production plays a crucial role for both regional and national economy, since it represents the 3% of the Gross Domestic Product (GDP) of the region, with an Economic Land Productivity (i.e., €/ha of cultivated crops considering their market prices) equal to 7,7% of the national production (Regione Puglia, 2013). It is characterized by a large variety of crops: the main cultivated ones are durum wheat, vineyard, olive trees and vegetable. The olive trees are the most characteristic factor of the regional agricultural landscape (**Error! Reference source not found.**). Figure 7, Figure 8 and 9 show the spatial distribution of the vineyard, durum wheat and the horticultures productions, respectively.

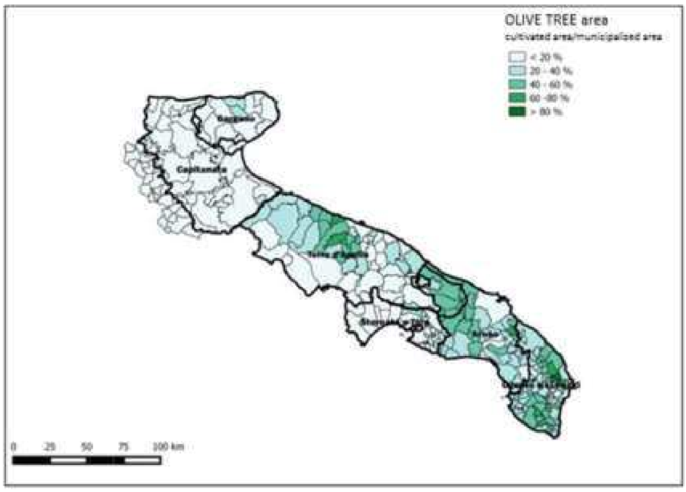


Figure 6*: Spatial distribution of olive trees production adapted from (AdB Puglia, 2013).*

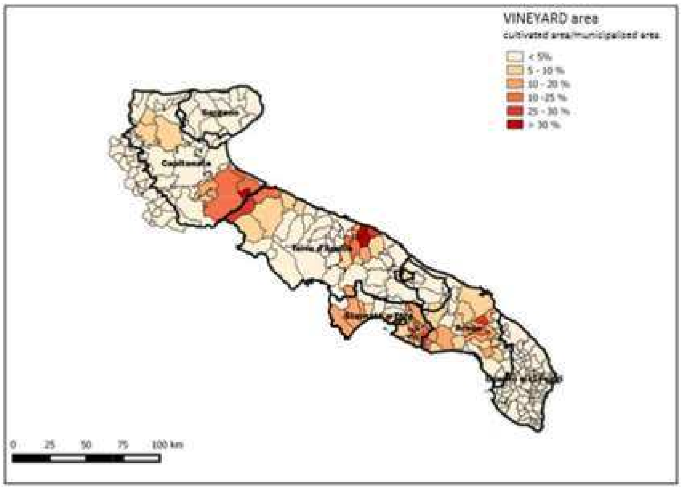


Figure 7: Spatial distribution of vineyard production adapted from(AdB Puglia, 2013).

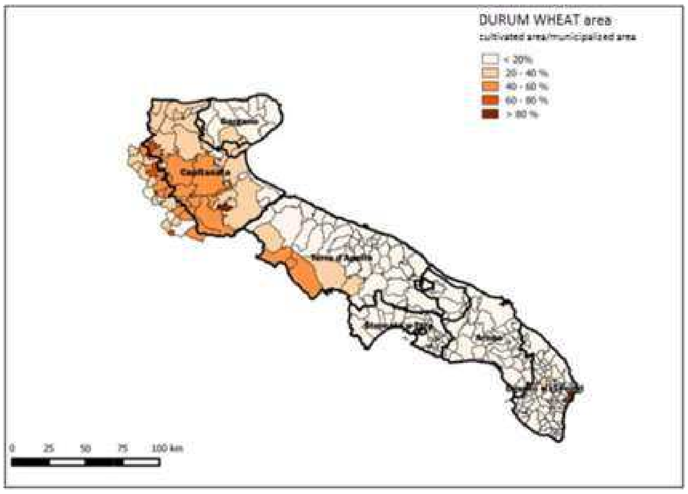


Figure 8: Spatial distribution of durum wheat production adapted from (AdB Puglia, 2013).

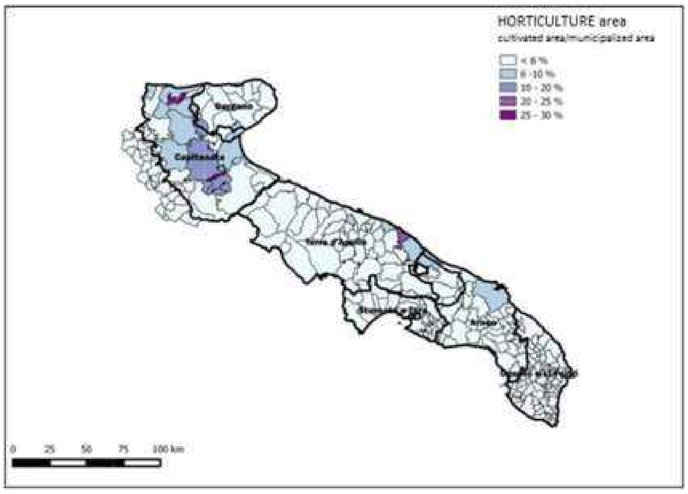


Figure 9: Spatial distribution of horticulture production adapted from (AdB Puglia, 2013).

3.3 Irrigation water management in Puglia

Probably, the major constraint to the social and economic development of the region is the water scarcity issues reated to climatic conditions and the low water supply capacity of surface water bodies (Portoghese *et al.*, 2013), hence a sustainable management of irrigation water is an key driver. In Puglia, irrigation water is usually managed by public entities (user association called consortia) that provide also for the preservation of the natural environment and for ensuring an adequate technical and administrative assistance to farmers. Within the region, six consortia exist namely: Consorzio di Bonifica della Capitanata, Consorzio di Bonifica del Gargano, Consorzio di Terre d'Apulia, Consorzio di Bonifica di Stornara e Tara, Consorzio di Bonifica Arneo and Consorzio di Bonifica Ugento li Foggi. In addition, a regional agency, nemed ARIF, operates within the region. In the following, two case study, one in Capitanata region managed by the Consorzio di Bonifica della Capitanata, and the other, in the south, managed by ARIF, are described.

3.3.1. Capitanata case study

The Capitanata is semi-arid region extended within the province of Foggia for almost 455,000 ha, of which about 150,000 ha are managed by the Consorzio di Bonifica della Capitanata. Two irrigation district are estabilished within the administrative boundary of the consortium, called respectively the “Fortore” in the North and the “Sinistra Ofanto” in the South (Figure 10). The Fortore district covers about 100,000 ha and is further divided in: North Fortore, including 10 irrigated districts serving 20,709 users, and South Fortore, constituted by 7 irrigation districts serving 10,171 users. On the other hand, the Sinistra-Ofanto district covers about 50,000 ha and is divided in 21 irrigated districts serving 27,251 users.

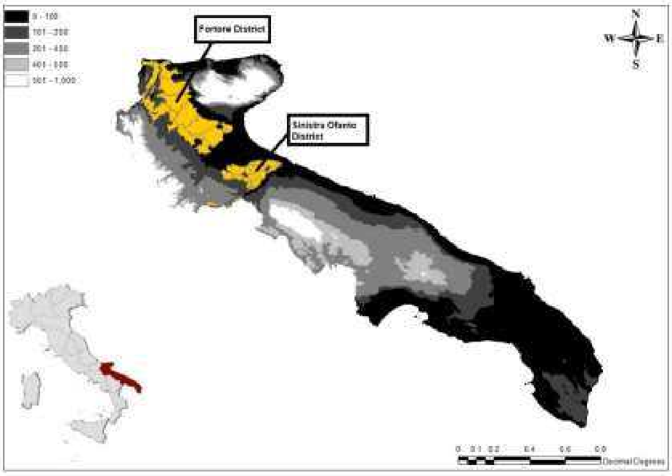


Figure 10: Consorzo di Bonifica della Capitanata districts.

The irrigation network is extended for 126,000 ha and is characterized by pressurized irrigation networks.The districts of North and South-Fortore are served by the Occhito and Capaccio dams, located on Fortore river and Celone stream and by the Vulgano stream via Mezzana Grande crossbeem.The Sinistra Ofanto district is supplied by the reservoirs of the Marana Capacciotti and San Pietro dams respectively on the Ofanto and Osento rivers.

According to the recent agricultural census (2010), among the more water-demanding crops, vegetables (above all tomatoes for industry) cover around 22000 ha, while table graphs are extended for about 6400 ha. Besides, olive orchards covering around 55000 ha, and an increasing trend from dry farming to groundwater irrigation was observed, although the deficit irrigation practice is generally applied.

The irrigation season generally starts on March 1st and ends on November 30th. The irrigation water distribution is carried out using on demand network, even if during peak period is sometimes provided in turn. The dispensing is volumetric, where the water meters (mechanical and/or electronic) have been installed, while in some areas where the pressure is not sufficient for the installation of the control devices, the drawdowns are allowed with delivery without pressure.Pricing is usually expressed on the basis of volumetric consumption, setting a cost of 0.12 €/mc of water withdrawn. This cost is established up assuming a standard water volume equal to 2,050 m^3 /ha. When the standard water volume is passed the price is 0,18 € /m^3 from 2,051 m^3/ha to , and 0,24 €/m^3 for values greater than 4,000 m^3/ha.

3.3.2. Alimini case study

The proposed methodology was also applied to an irrigation district located in the Puglia region (southern Italy), along the Adriatic coast nearby Otranto cape (Figure 11). From a geophysical viewpoint, two coastal lakes (Alimini lakes) constitute the water storage system, of which one is a brackish water body called Alimini Grande, while the other one is a freshwater lake called Alimini Piccolo or Fontanelle, and it has been used as an irrigation source since the 1950s due to its good water quality.
The average storage capacity is 1.2 Mm^3, although annual storage is influenced by a marked climate variability, with average annual precipitations of approximately 700 mm. Freshwater extraction for irrigation purposes causes rapid decreases in summer water level. Similarly, the aquifer is intensively exploited as a source of drinking (e.g., Masciopinto et al., 2007) and irrigation water (Portoghese *et al.*, 2013), with increasing concerns due to the potential impact for public health (Bagordo et al., 2016; De Donno et al. 2016).

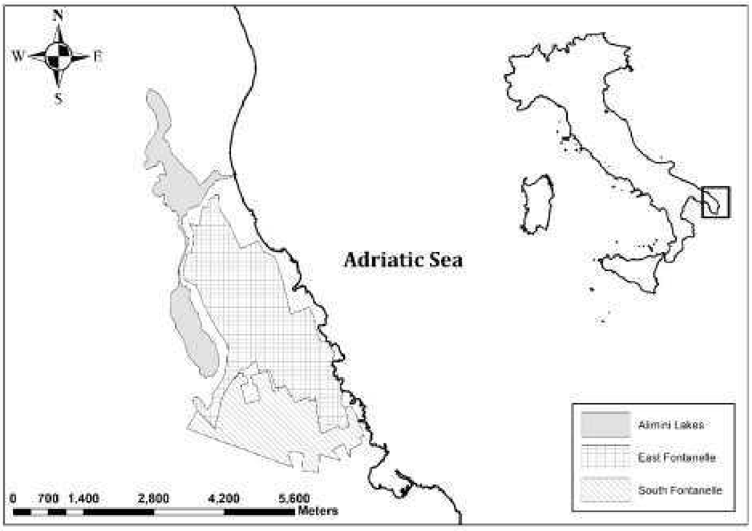


Figure 11: Alimini Piccolo Lake characteristics.

Focusing on agricultural activities, the irrigation district area (around 1000 ha) was originally supplied only by lake withdrawals supplying two distinct irrigation schemes called East Fontanelle (around 650 ha) and South Fontanelle (around 350 ha). Both systems were developed in the 1950s, with pressurized pipe networks and two reservoirs with a geodetic altitude of approximately 30 m a.s.l. During the last decades, the study area has experienced increases in groundwater withdrawals due to a general preference for on-farm water supply connected to private wells, also driven by the increasing market demand for vegetable crops. According to the recent agricultural census (2010), among the more water-demanding crops, vegetables (particularly tomatoes) cover around 220 ha, while vine plant nurseries are a developing enterprise, with 53 ha. Moreover, olive orchards covering around 2,000 ha, 700 of which fall within the district area. From 2013 to 2014, a monitoring campaign was undertaken on the lake catchment and the surrounding area. Particularly, lake withdrawals for irrigation and drinking purposes were directly monitored, together with groundwater table and salinity. Other data were collected for 2007-2012 from the irrigation district authority. Over the investigated period, an average of 0.27 Mm^3 were yearly withdrawn from the lake, and more than half (0.15 Mm^3) used for irrigation. Compared to the original irrigation plan developed in the 1950s (reporting a 1.2 Mm^3 of average lake withdrawal), lake withdrawals currently reveal a diffuse and consistent exploitation of groundwater resources to fulfil irrigation water demand. This could be due to the good quality and accessibility of groundwater, and probably also to the quite high value of the water tariff (about 0.31€/m^3) applied in the last decade.

CHAPTER 4
METHODOLOGY APPLICATION IN PUGLIA REGION

> *"Success is a science;*
> *if you have the conditions, you get the result"*
>
> *Oscar Wilde*

4.1 Understanding system dynamic

For studying the complex dynamism of the irrigation water management system, a conceptual model of the Capitanata system has been developed. It is worth noting that the methodology implemented is not restricted to this case study, but its model flexibility supports its adaptation to a wider range of case studies.

As demonstrated by Giordano et al. (2016) a dense network of relationships among different decisional actors constitutes the Capitanata system. Specifically, each actor operates in the system according with own interests and its behaviour strongly influences the behaviours of the other involved stakeholders. As results, different behaviours overlapping within the system and conditioning its dynamic. Furthermore the above cited paper demonstrates that decision-makers at different level usually are either unaware of being part of a densely interconnected network of decision-makers or neglect the impact of this network on their own decisions (Giordano *et al.*, 2013, 2015; Portoghese *et al.*, 2013). Therefore, moving from the above mentioned results, the identification of the main involved stakeholders in a given irrigation water management system and accordingly the elicitation of their mental models has been carried out. In detail, three main actors related to farmers, water agency (that is, the organization responsible for the management of the public irrigation system), and regional authority, have been selected as interested in irrigation water management process, each of which operate at different decision-making scales. Table 1 summarize the main output of the stakeholder analysis.

DECISIONAL ACTORS	PURPOSES	INTEREST	DECISION-MAKING SCALE
Farmers	Farm's profit maximization	Water resources availability according with the crop water requirements for the entire irrigation season	Farm scale
Water Agency	Correct distribution of available water among farmers along the entire irrigation season	Limiting over-exploitation of water resources in water scarcity conditions	Consortium scale
Regional Authority	Groundwater source protection	Control and monitoring of groundwater exploitation	Regional scale

Table 1: Output of stakeholders' analysis

The results of stakeholder analysis were used to implement actor's mental model. Particularly, the results of individual semi-structured interviews, carried out by Giordano *et al.*, (2013, 2015) and Portoghese *et al.*, (2013), were implemented in CLD's to elicit stakeholder's understanding of irrigation water management in drought conditions, and of the role played by the other decisional-actors.

4.1.1 Farmer’s mental model

As shown in Table 1, the main farmer’s goal is to maximize the profit (i. e., expected farm profit in

) defined as the difference between the economic land productivity (i.e., defined as product among crop market price and yield), and irrigation costs (i.e. sum of irrigation water cost for water abstraction by water management authority and ground water cost). In further details, the cropping pattern of irrigation season is defined by farmers every year mainly in October. The key elements influencing this decision are i) water storage into reservoir of water agency at the moment when they take a decision, and ii) crop market price. However, as demonstrated in Giordano et al. (2016), farmers perceive market conditions as more influential than the water availability. Consequently, in case of low market price of the rain-fed crop, the farmers would perceive the irrigated crop as more attractive than the rain-fed crop. As result, the economic land productivity affects farmer's decision making process, which leads to investing in more profitable crops with a consequent increase in the irrigated area in order to increase the crop yield. However, the increase in irrigated areas results in water demand rising (i. e. irrigation requirement). On the other hand, the limited water availability is perceived by farmers as a limiting factor and as consequence they react searching alternative water sources to fulfil crop water requirement. From a dynamic point of view, the farmer's mental model can be described by three balancing loop B1, B2 and B3 and one reinforcing loop R1.

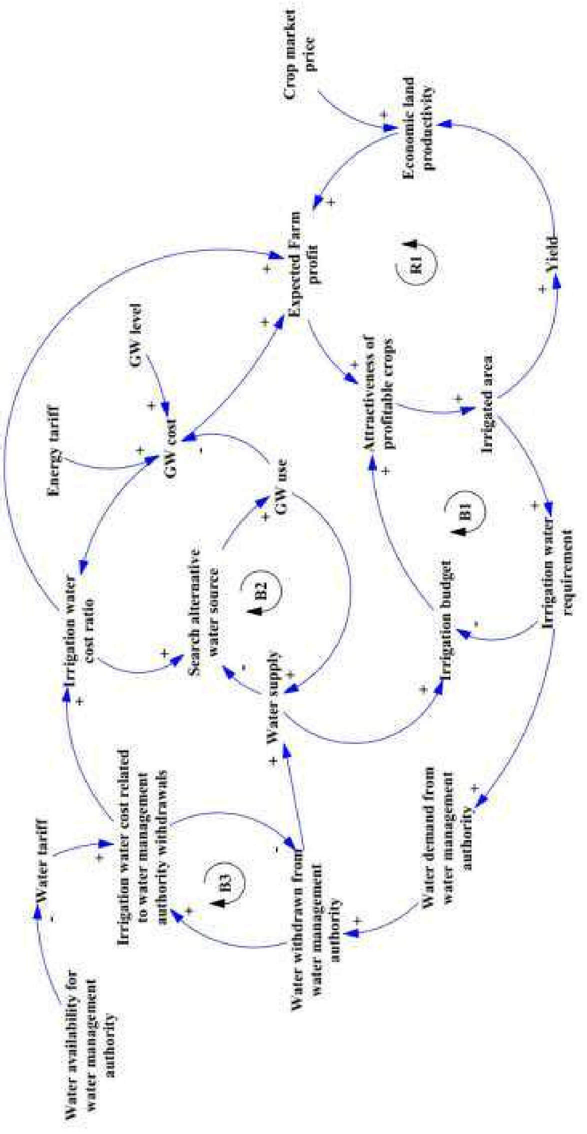


Figure 12: Framer’s mental model

4.1.2 Water agency mental model

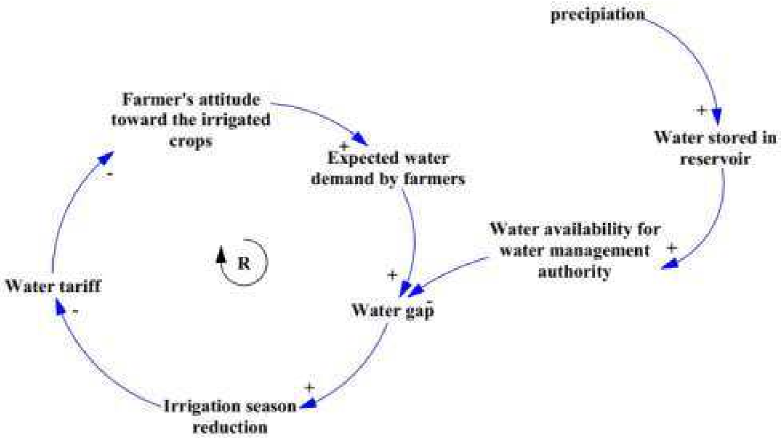


Figure 13 shown the water agency mental model. In detail, the main objective of this Water Agency is to ensure a fair distribution of water among farmers. Therefore, in water scarcity conditions, the attitude of farmers towards irrigated crops, is perceived by water agency as a threat to the achievement of their objective, resulting in a water gap, which is defined as difference between the water demand of farmers expected by

the water agency (i. e., Expected water demand by farmers in

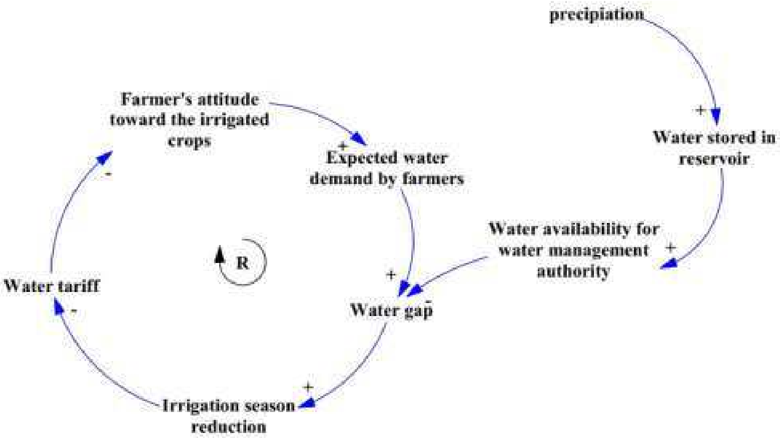


Figure 13) and their water availability. Consequently, the water gap rising lead water agency authority to reduce irrigation season period and, accordingly, increasing water tariff, to limit exploitation of water resources. From a dynamic point of view, this type of dynamics is represented by a ring of reinforcing type "R".

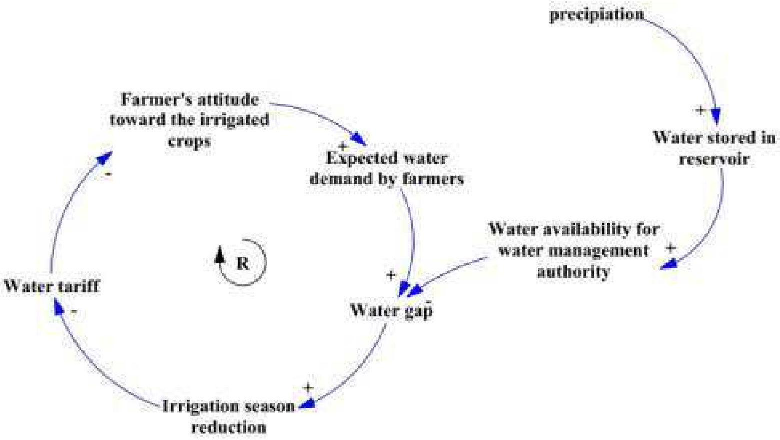


Figure *13*: Water management authority mental model

4.1.3 Regional Authority mental model

The Regional authority objective is to limit the over-exploitation of groundwater resources. Therefore, the increase in irrigated areas poses a threat to the groundwater status due to increased water demand. Uncontrolled use of groundwater, in order to satisfy water demand, results in a lowering of groundwater and a deterioration of groundwater quality, particularly evident in the coastal areas. Therefore, a deterioration in the quality of groundwater results in an over-exploitation of the groundwater. As a result, the regional authority reacts by imposing a limit on the use of groundwater. From a dynamic point of view, this mental model is constituted by two distinct loops as shown in Figure 14: a balancing loop B and a reinforcing loop R.

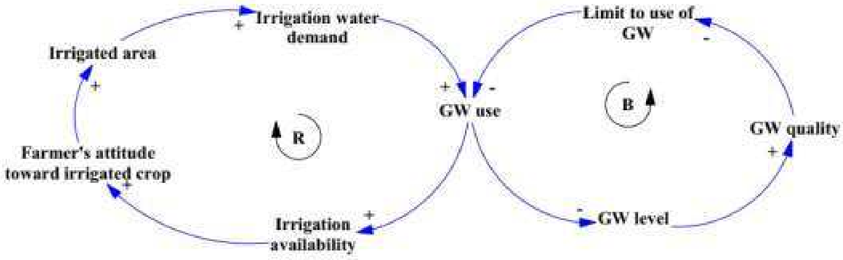


Figure *14*: Regional authority mental model

4.1.4 Analysis of the system’s dynamic

In order to analyse the dynamic of the system and to identify the main elements conditioning sustainable management of water resources, a conceptual model of the system’s dynamic has been developed by integrating the individual CLD’s and introducing other variables allowing the integration of different decision-making scale. Figure 15 shows the CLD of the irrigation water management system.

Particularly, the CLD of the system demonstrated that mutual influences exist among the actors involved, whose behaviour is influenced by external drivers (e,g., crop market price, water availability). The interaction among different water users activates three intertwined dynamics related to the irrigation water demand (i.e., IWD marked in red), to the irrigation water withdrawals (i.e., IWW marked in violet) and to the irrigation water cost (i.e., IWC marked in green) (Figure 16). Another important dynamic activated within the system is related to the energy consumption (i.e. EC marked in orange), which mainly depends on water withdrawals and is influenced by farmer’s behaviour.

The IWD dynamic is mainly related to the crop choice and is influenced by the water availability and market condition (e.g., crop market prices), which are the main variables contributing to the farmer’s crop choice (i.e., irrigated area). Two loops are dominant in this dynamic: a balancing loop (B1 – related to irrigation crop requirements) and a reinforcing loop (R1 – related to the connection between crops and associated profit) which, from a dynamic point of view, can be conceptualized as a “limited to growth” archetype according to definition provided by Vennix, (1996). The IWD dynamic has significant cascading impacts on the other two dynamics. Specifically, the IWW module describes the dynamic of water withdrawals from different water sources (i.e. surface and groundwater source) and two loops (B2 and B3 respectively) define the interconnected and interdependent behaviour. When groundwater pumping is more affordable than using the surface water, the use of the aquifer becomes more relevant. As a result, groundwater may be subjected to over-exploitation, and both water quality and quantity may be affected (loop B4). The large amount of water abstracted from groundwater source is also associated to an high-energy consumption with cascading impacts on environment. The IWW dynamic also strongly influences the IWC dynamic, since water withdrawals have important impacts on farmers' costs, which in turn influences the profit in the IWD dynamic (loops B2 and B3). In table 2 are summarized the loops activated within the system, while the variable list is in appendix A.

LOOP	DYNAMIC	POLARITY	VARIABLES
R1	IWD	+	Expected farm profit; Attractiveness of profitable crops; Irrigated area; Yield; Economic land productivity;
B1	IWD	-	Irrigated area; Crop Water Requirement; Irrigation water requirement; Irrigation budget; Attractiveness of profitable crops;
B2	IWW	-	Water supply; Search of alternative water source; GW use;
B3	IWW and IWC	-	Water distributed by water management authority; Irrigation water cost;
B4	IWC	-	GW use; GW level; GW quality; Limit to use GW;

Table 2: List of the loops activated within the system

In conclusion, as emerged from the analysis of the system's dynamic, the main factors conditioning sustainable management of water resources are related to:

i) economic land productivity influenced by the external driver of crop market price;

ii) water availability depending on the external driver of precipitation which in turn influence farmer's behaviour in searching alternative water source in case of limited water availability,

iii) irrigation water cost (i.e., water cost related on both surface and ground water withdrawals) depending on water and energy tariff.

In order to provide a quantitative assessment of the irrigation practice implication, summarizing the dynamic of the system, the indicator-based approach, as explained in chapter 2, has been applied in different context of Puglia Region, as explained in the next section. While Appendix E provide a detailed explanation of the CLD validation.

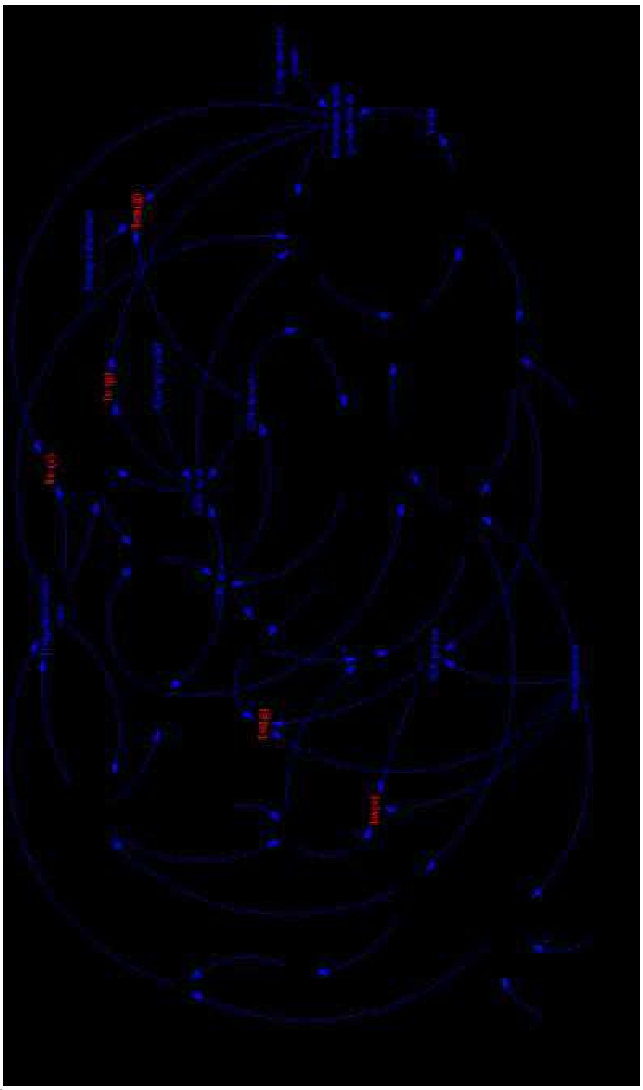


Figure 15: System's dynamic in red are marked the indicators selected for evaluate the state of the system

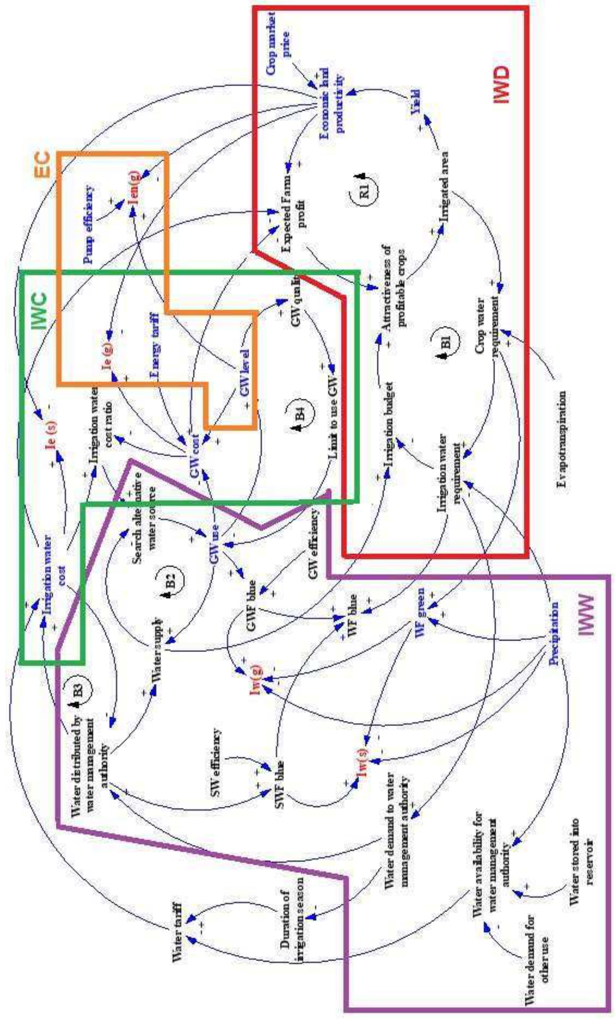


Figure *16*: Dynamics of the system: Irrigation Water Demand dynamic (red line); Irrigation Water Withdrawals (violet line), Irrigation Water Cost dynamic (green line), and Energy Consumption dynamic (orange line)

4.2 Sustainability assessment of irrigation practice

The indicator-based approach, as explained in chapter 2 (section 2.2) has been implemented in two areas, in order to test its applicability in different contexts. Particularly, it was first applied in a small irrigation district in Salento peninsula, considering the agricultural production of Alimini Piccolo lake area and then at larger scale in Capitanata in northern Puglia. Therefore, for providing the reader a detailed description of each considered district, the following subsections summarize the main characteristics of each area and the main assumptions adopted for the methodology application, whereas the other subsections summarize the results of indicator-based approach implementation in each considered area.

4.2.1 Sustainability assessment of irrigation practice in the area close to Alimini Piccolo lake

The sustainability assessment of the irrigation practice considering the case study named Alimini Piccolo lake has been carried out in the period from 2007 to 2014. Adopting the agricultural land cover information available from a recent census (i.e., 2010), the CropWat® software (Allen, 1998) was used to estimate crop water balance, including the green and blue water footprint, assuming monthly climate observations from a nearby station and soil parameters from the regional pedological map. For further information on the data used in CropWat® software, please refer to Appendix B.1. The results from crop water balance simulations, coupled with monitoring data, have allowed to evaluate surface and groundwater withdrawals, assuming GI_s equal to the water volumes distributed to farms. To evaluate the energy consumption for irrigation, a hydraulic head equal to the altitude of reservoirs H_g was assumed for the lake pumping stations (30 m) and an equal hydraulic head (30 m) for groundwater withdrawals, as given by the average water table depth (10 m) and the sprinkler operating pressure head (20 m). The monitoring campaign has allowed to estimate the parameters related to water conveyance efficiency (e_c, discussed in Section 2.2.1) and pumping efficiency (η_s, discussed in Section 2.2.2). The former was estimated based on monitoring data related to water withdrawals and the volumes distributed to the farms, during the irrigation season 2014 (i.e., April-September). Therefore, according to the methodology proposed by Hsiao et al.(2007), the ratio between the amount of water distributed to the farms and that of water withdrawn from the lake was adopted as a measure of the total efficiency, e_c. The monitoring campaign provided values of water conveyance efficiency ranging between *0.85* and *0.58*, depending on hydraulic features and specific operating conditions. Therefore, an average water conveyance efficiency (*0.68*) was considered. A similar approach was adopted for the evaluation of η_s, which was estimated through the calibration of the pump rating curves obtained during the flow tests carried out during the monitoring phase. Pump efficiency was estimated according to Barutçu et al. (2007) as a ratio between hydraulic and electric power, under five operating conditions. The resulting pump efficiency ranged between *0.70* and *0.45* and an average value of *0.58* was assumed. In the following section, the results of the proposed index-based methodology are summarized, while a list of the main used symbols is presented in Appendix C.

4.2.1.1 Irrigation Water Footprint Index

In terms of irrigation requirements, although olive orchards are the most diffused crop in the area, they present the lowest irrigation requirements ($\approx$690 m^3/ha). The irrigation requirements of tomatoes ($\approx$4200 m^3/ha) and, similarly, vineyards ($\approx$3600 m^3/ha) are significantly higher and, in both cases, relevant water abstraction from groundwater is expected. In fact, the analysis of the water volumes distributed to farms within the irrigation district showed that the amount of water supplied from the lake accounts for only 10% of the total, and thus approximately 90% of the water volume for irrigation comes from groundwater. The water footprint results show that, although the olive orchards have the highest total water footprint ($\approx$ 7.98 Mm^3), the green component WF_{green} is the most relevant ($\approx$ 6.62 Mm^3). It is worth to mention that because most of olive orchards areas fall outside the irrigation district, it is reasonable assuming that their water requirements are completely satisfied by groundwater. Therefore, the GWF_{blue} for olive trees is the only component of WF_{blue} and equal to 1.36 Mm^3. On the other hand, with reference to tomatoes and vineyards, although they have a lower total water footprint due to the smaller cultivated areas, their blue component WF_{blue} (0.92 Mm^3 and 0.20 Mm^3 respectively) is much higher than the WF_{green}. Both crops are partially irrigated from surface water and partially from groundwater. The GWF_{blue} was identified in both cases as the prevalent component of the WF_{blue} (approximately 0.86 Mm^3 for tomatoes and 0.18 Mm^3 for vineyards). From the above analysis, the irrigation water footprint index (from Eqs. (1), (4), (5)) was calculated for all crops over the entire period of investigation (2007-2014). Figure 17 reports the $I_{w(s)}$ and $I_{w(g)}$ trends that clearly highlight as tomatoes and vineyards have generally comparable impacts on surface and groundwater resources. Despite a slightly lower irrigation requirement, the water consumption of the vineyards is even higher during some years (e.g., 2013), mainly due to specific climatic conditions (i.e., the distribution of the rainfall during the irrigation season) and to the different growing seasons for the two crops (longer for the vineyard). $I_{w(g)}$ is higher than $I_{w(s)}$ for both crops, denoting that groundwater withdrawal is approximately 90% of the global withdrawal for irrigation. It is worth noting that, as expected, the methodology suggests major impacts of both crops in the driest years (i.e., 2008 and 2013). The additional comparison with olive orchards highlights that, although their total GWF_{blue} is higher, the relative impact expressed in terms of $I_{w(g)}$ is significantly lower (average value of 0.19). The average values of the main parameters are summarized in Table 3.

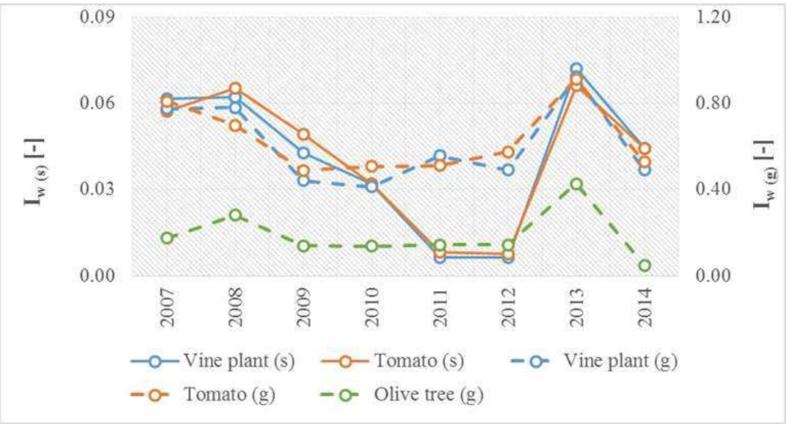


Figure *17*: Irrigation Water Footprint Index during 2007-2014, for tomatoes (orange lines), vine plants (blue lines) and olive trees (green lines). The dashed lines identify the results of the Irrigation Water Footprint index related to groundwater abstraction ($I_{w(g)}$), whereas the continuous one the results of irrigation water footprint index related to surface water abstraction ($I_{w(s)}$).

CROP	**WF_{blue} [Mm^3]**	**WF_{green} [Mm^3]**	**SWF_{blue} [Mm^3]**	**GWF_{blue} [Mm^3]**	**$I_{w(s)}$ [-]**	**$I_{w(g)}$ [-]**
Olive	1.35	6.62	-	1.35	**-**	**0.19**
Vine	0.20	0.09	0.01	0.18	**0.05**	**0.60**
Tomato	0.92	0.24	0.06	0.86	**0.05**	**0.62**

Table 3: Average values, calculated from 2007 to 2014, of the main quantities under investigation: blue and green water footprint (WF_{blue},, WF_{green}), surface and groundwater footprint blue component (SWF_{blue}, GWF_{blue}), Irrigation Water Footprint index ($I_{w(s)}$ and $I_{w(g)}$).

4.2.1.2 Energy Footprint for Irrigation Index

The index was calculated relating the energy used for pumping water from a specific source and the required pressure to economic land productivity. The economic land productivity was calculated for all the crops under investigation, showing that although the olive orchards are the most extensive crop in terms of area (88% of the total area), they are also the less profitable ones, with an economic land productivity of 1,334 €/ha. Instead, tomato crop is the most profitable (≈17,500 €/ha) and cover about 10% of the total area. Furthermore, the E_{lp} of vineyard, which covers only the 2% of the total area, is approximately 10,070 €/ha. In terms of energy requirements, it is worth considering that, the groundwater withdrawals are the 90% of the total volume but, referring to the unit values of energy consumed, $E_{a(g)}$ is lower than $E_{a(s)}$. This is due to the higher water efficiency of groundwater supply systems. The values founded for tomato and vineyard are similar (see Table 4). The energy consumption associated with the irrigation of olive trees is significantly lower (average $E_{a(g)}$ ≈172.6 kWh/ha).

The Energy Footprint for Irrigation Index $I_{en(s)}$ and $I_{en(g)}$, according to Eqs. (9) and (10), are represented in Figure 18. Referring to groundwater withdrawals, the olive tree cultivation is associated to the highest index average value (≈ 0.13 kWh/€), which is comparable with the value obtained for vineyards (≈0.10 kWh/€) and higher than the tomato value (≈0.06 kWh/€). Similarly, referring to surface withdrawals, the vineyard value is higher than the corresponding value obtained for tomato. These results suggest that, although the irrigation of some crops (e.g., tomatoes) may have higher environmental impacts being high energy demanding, they might be considered sustainable due to higher economic profitability. The above cited results are summarized in Table 4.

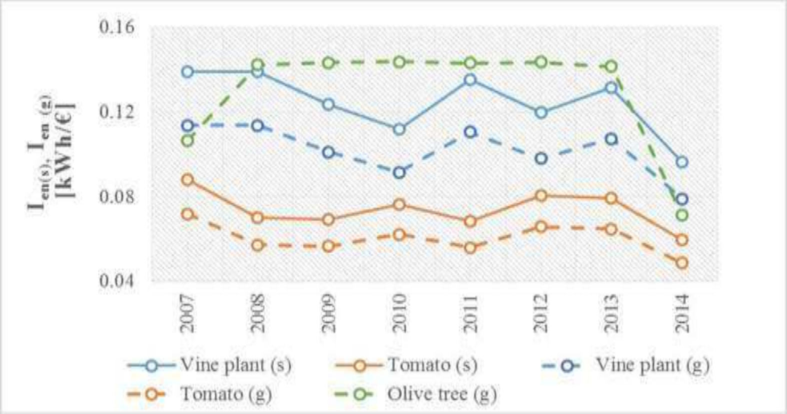


Figure *18*: Values of Energy Footprint for Irrigation Index. The values of the Energy Footprint for Irrigation Index I_{en} are plotted for each crop over the entire period (2007-2014) Both values associated to surface $I_{en(s)}$ and groundwater withdrawals $I_{en(g)}$ are plotted with continuous and dashed lines respectively

CROP	$E_{a(s)}$ **[kWh/ha]**	$E_{a(g)}$ **[kWh/ha]**	E_{lp} **[€/ha]**	$I_{en(s)}$ **[kWh/€]**	$I_{en(g)}$ **[kWh/€]**
Olive	-	172.6	1,334	**-**	**0.13**
Vine	1,254.1	1,507.7	10,070	**0.12**	**0.10**
Tomato	1,293.7	1,025.4	17,500	**0.07**	**0.06**

Table 4: Summary of average values for the unit Energy Consumption Index, and the Energy Footprint Index for the investigated crops.

4.2.1.3 Irrigation Water-Cost Footprint Index

The analysis of the irrigation water cost, referring to both water sources demonstrated that, due to their high irrigation demand, tomatoes and vineyards have an high unit surface water cost (average $C_{w(s)}$ values respectively equal to 1,946 €/ha and to 1,886 €/ha). Comparable results were obtained for both crops in terms of groundwater costs (average values of 157 €/ha and 152 €/ha respectively), despite the latter ones being remarkably lower. The groundwater cost was also computed for olive orchards, showing the lowest value (≈26 €/ha). The main findings in terms of $I_{e(s)}$ and $I_{e(g)}$, according to the Eqs. (12) – (13), are in Figure 19. The production of tomatoes is associated with lower values of the index, since it is characterized by higher economic profitability, both in terms of surface water and groundwater. Conversely, olive trees present a low average $I_{e(g)}$ value (approximately 0.02) due to their limited economic profitability. The vineyards show intermediate values of the index. The results of the irrigation water-cost footprint also show that, for a fixed crop, the values of $I_{e(g)}$ are significantly lower than those of $I_{e(s)}$. This is due to the lower groundwater cost compared to surface withdrawals (approximately 10%). These different costs associated to the water abstraction sources justify the significantly higher volumes of water abstracted from groundwater.

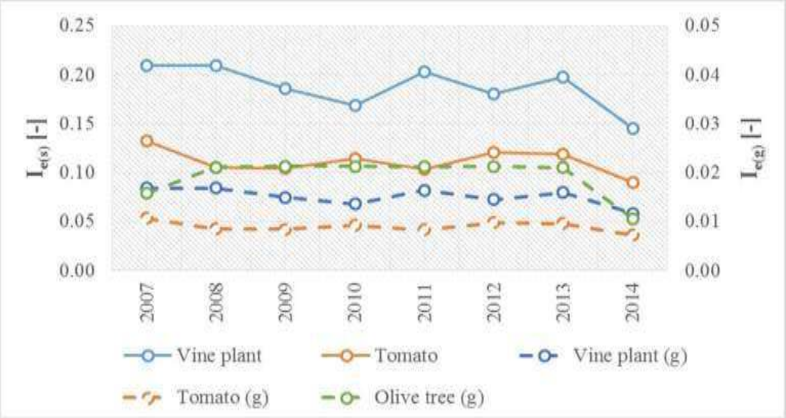


Figure *19*: Values of the Water Cost Footprint Index. The values of I_e are plotted for each crop over the entire period (2007 - 2014). Both the values associated to surface $I_{e(s)}$ and groundwater withdrawals $I_{e(g)}$ are plotted, with continuous and dashed lines respectively.

Table 5 summarizes the results for each crop, in terms of the average values of water cost, economic land productivity and Water-Cost Footprint index.

CROP	**$C_{w(s)}$ [€/ha]**	**$C_{w(g)}$ [€/ha]**	**$I_{e(s)}$ [-]**	**$I_{e(g)}$ [-]**
Olive	-	25.63	**-**	**0.02**
Vine	886.32	152.27	**0.19**	**0.02**
Tomato	945.87	157.09	**0.11**	**0.01**

Table 5: Summary of average values of unit water cost, economic land productivity and Water-Cost Footprint Index for the investigated crops.

4.2.1.4 Comparative analysis of the indices assessing irrigation sustainability and related impacts

The comparative analysis of the three indices allows highlighting their specific impacts, benefits, and trade-offs related to the irrigation practices for different crops, according to the WEFN multi-dimensional approach. This supports directly the related key aspects connected with the production of either a specific crop in different areas/conditions or different crops in the same area. Two analyses with different purposes have been carried out. First, the three indices were compared in a disaggregated form, considering the two water sources (Figure 20), for identifying the implications of such a choice in both economic and energy terms. Second, a comparison was performed using a hybrid version of the indices (Figure 21) to highlight the benefits and impacts generated by the cultivation of different crops in a given area, taking into account the combined use of the two water sources. The results of both analyses are plotted on a spider-graph. To allow a better visualization of the results, the graph includes the logarithmic of each normalized index, where the normalization has been done with respect to the relative maximum value calculated (see Appendix C). The graph also includes an additional parameter, the normalized crop area, calculated with respect to the total cultivated area. The area represents a “scale” factor of the impacts estimated through the indices, accounting for the spatial extension of the specific crops. As shown in Figure 20, the comparative analysis of the indices clearly demonstrates that groundwater abstraction is largely preferred in the area, as suggested by the higher values of $I_{w(g)}$ compared to the corresponding $I_{w(s)}$. Although uncontrolled use could cause potential overexploitation, with significant environmental impacts, groundwaters are crucial for farmers, due to the higher accessibility associated with lower costs ($I_{e(g)} < I_{e(s)}$). The energy requirements associated with the two water sources are comparable, resulting in a similar impact ($I_{en(s)} \sim I_{en(g)}$), although it is evident that such values also depend on both the pumping and conveyance efficiencies characterizing the infrastructure.

Focusing on single crops, olive production shows the lowest impacts in terms of irrigation due to its low water requirements, which are fully satisfied by groundwater

($I_{w(s)}=0$). Conversely, its impacts, expressed in terms of the energy and irrigation water cost footprint indices are high, in both cases, due to its low economic profitability. Instead, the tomato production requires a large irrigation volume, mainly derived from groundwater. Nonetheless, the irrigation water cost and the energy footprints for irrigation values reveal the quite high profitability of this crop due to the high economic land productivity. Similarly, the impact of vineyard production on surface and, particularly, groundwater sources is high. The lower economic land productivity of this crop, compared to the tomato, results in higher values for both I_e and I_{en}.

Focusing on water resources exploitation, this comparative analysis confirms some of the results of several studies carried out in the same region (e.g. Giordano et al., 2015; Zingaro et al., 2017,a); above all the irrigation water cost, compared with the economic land productivity of specific crops, is one of the main drivers influencing water source selection (Smidt *et al.*, 2016). This, along with the higher accessibility of groundwater as on-farm water supply, explains why groundwater abstractions accounts for 90% of the total water withdrawals in the investigated area.

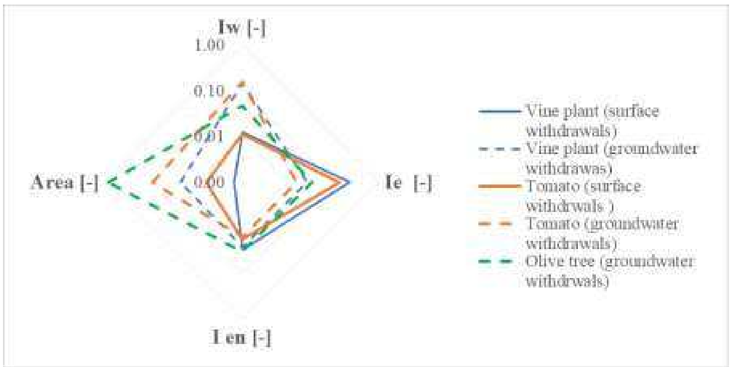


Figure *20*: Footprint index-based approach for WEFN assessment of agricultural production. The graph includes the logarithmic values of normalized index. Dashed lines refer to groundwater withdrawals, while continuous lines refer to surface water.

The results of the “hybrid” version of the indices, calculated considering the actual ratio between surface and groundwater irrigations in the study area, are represented in a spider-graph (Figure 21) whose numerical values are reported in Table 6. Considering the three investigated crops, different profiles can be identified and described within the WEFN framework. The tomato crop is characterized by the highest value of I_w (0.67), and the lowest I_{en} (0.06) and I_e (0.015) values. These values are strictly related to the high irrigation requirements, which are ”balanced” in terms of energy consumption and water costs owing to the high land productivity. For vineyards, the high values of I_w (0.65) and I_e (0.03), along with values of I_{en} (0.10) are due to the quite high irrigation requirements and economic land productivity. It is worth mentioning that this crop selection can be also explained by local farmers’ specialization in growing and marketing this niche product. The olive grove profile is associated to low I_w values (0.19), high I_{en} values (0.13), and intermediate I_e values. In conclusion, olive groves appear as the most sustainable production due to their low irrigation requirement and water-stress tolerance, even if there are low values of land productivity due to high energy and water cost indices.

It is worth noting that, besides the drivers included in the methodology, other local and external factors, such as traditional olive production and/or the Common Agricultural Policy subsides may influence the attractiveness of a specific crop (Zingaro et al. 2017a).

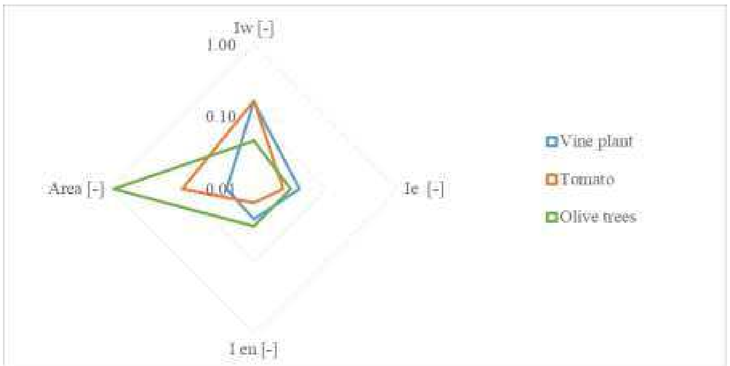


Figure *21*: Footprint index based approach for WEFN assessment of Fontanelle Lake. The values of the indices are computed considering a ‘hybrid’ configuration depending on the effective ratio between groundwater and surface water. The graph includes the logarithmic values of normalized index.

Comparative analysis hybrid version				
CROP	**I_W [-]**	**I_{en} [kWh/€]**	**I_e [-]**	**AREA [ha]**
Vineyards	*0.65*	*0.10*	*0.03*	*53*
Tomato	*0.67*	*0.06*	*0.015*	*218*
Olive tree	*0.19*	*0.13*	*0.019*	*1,946.92*

Table 6: Summary of the Footprint Indices for the investigated crops (hybrid version).

4.2.2 Sustainability assessment of irrigation practice in Capitanata plain

The sustainability assessment for this large area has been carried out considering the 2001-2011 period, involving Fortore and Sinistra Ofanto irrigation area. For this aim, data related to agricultural production (i.e., yield and cultivated area) have been collected from Italian National Institute of Statistic (i.e., ISTAT), whereas data related to crop market price have been collected from Chamber of Commerce of Foggia. At the end, due to high extension of the area, in order to assess its climatic characteristics, a spatial analysis of precipitation and temperatures through the Thiessen Polygons method was used. Particularly, this analysis aimed at defining a homogeneous "virtual" station station, for which the historical series (i.e., from 1969 to 2011) of rainfall and temperatures have been reconstructed. The annual irrigation water volume, as declared by Consorzio per la Bonifica della Capitanata, has allowed to evaluate surface and groundwater withdrawals using Eq.(6), assuming GI_s equal to the distributed water volumes to farmers. It worth noting that the amount of energy consumed for irrigation withdrawals from dams is negligible, being it distributed by gravity. On the contrary, to evaluate the energy consumption, a hydraulic head of 66.50 m was assumed for groundwater withdrawals, as given by the average water table depth (40 m) and the sprinkler operating pressure (26.5 m), whereas water conveyance efficiency (e_c, discussed in Section 2.2.1) was estimated based on data related to withdrawals and the distributed water volumes, during the analysed period. According to the methodology proposed by Hsiao et al.(2007), the ratio between the amount of water distributed to the farms and that of water withdrawn from the dam was adopted as a measure of the total efficiency, $e_{c;}$ it was assumed equal to *0.87*. Referring to the pumps efficiency it was assumed equal to *0.50*. In the following section, the results of the proposed index-based methodology are summarized. Moreover, in this case study the analysis has been carried out considering that only the minimum water supply (i.e., 2050 m^3/ha) is withdrawn from consortium, as resulted from interviews with farmers operating within this area. This farmers' behaviour is justified by the limited volume of water guaranteed by the water agency that is insufficient to satisfy the irrigation demand. Moreover, it also depends by the high affordability of groundwater pumping, which was estimated approximately equal to 0.06 €/m^3 considering only the electric cost due to the energy tariff (i.e., 0.15 €/kWh).

4.2.2.1 Irrigation Water Footprint Index

Concerning the irrigation requirements, the results highlight that the olive orchards, which are the most diffused crop in the considered area, have lowest irrigation requirements ($\approx$1268 m^3/ha), since they are mainly fed by rainwater with few applications of irrigation. On the other hand, the irrigation requirements of tomatoes ($\approx$4760 m^3/ha) and, similarly, vineyards ($\approx$3100 m^3/ha) are significantly higher. Therefore, due to the limited water availability stored in the dams and available for irrigation (i.e., about 77 Mm^3), in both cases, imposes a relevant water abstraction from groundwater. Similar results are obtained from water footprint: the green component WF_{green} of the olive orchards *is* the most relevant ($\approx$ 224 Mm^3), higher than the blue component WF_{blue} ($\approx$ 45 Mm^3). Conversely, referring to tomatoes and vineyards the blue component WF_{blue} ($\approx$108 Mm^3 and $\approx$17 Mm^3 respectively) is much higher than the WF_{green} being both crops partially irrigated from surface water and partially from groundwater. The GWF_{blue} was identified in both cases as the prevalent component of the WF_{blue} (approximately $\approx$79 Mm^3 for processing tomatoes and 10.19 Mm^3 for vineyards). The irrigation water footprint index (from Eqs. (1), (4), (5)) was calculated for all crops over the entire period of investigation (2000-2011). Figure 22 proposes a detailed analysis of $I_{w(s)}$ and $I_{w(g)}$ trends, which clearly highlight that processing tomatoes and vine plants have comparable impacts on surface and groundwater resources. Despite a slightly lower irrigation requirement, the water consumption of the vineyard is higher in some years (e.g., 2004, 2006 and 2009), due to specific climatic conditions (i.e., the distribution of the rainfall during the irrigation season) and to different growing seasons. The comparison with olive orchards highlights that the relative impact expressed in terms of $I_{w(g)}$ are similar to the vineyard (average value of 0.19). This is due to the fact that the cultivated area covered by olives orchards is higher than vine plant one and this mainly affects the $GWF_{blu\ e}$ component values. All the values of the main parameters are summarized in Table 7.

CROP	WF_{blue} [Mm^3]	WF_{green} [Mm^3]	SWF_{blue} [Mm^3]	GWF_{blue} [Mm^3]	S_w [Mm^3]	$I_{w(s)}$ [-]	$I_{w(g)}$ [-]
Olive	44.74	224.4	-	44.79	-	**-**	**0.62**
Vine	17.12	9.90	6.93	10.19	8.93	**0.30**	**0.42**
Tomato	108.2	31.35	29.22	78.98	37.79	**0.28**	**0.78**

Table 7: Average values, calculated from 2001 to 2011, of the main quantities under investigation: blue and green water footprint ($WF_{blue,}$, WF_{green}), surface and groundwater footprint blue component (SWF_{blue}, GWF_{blue}), gross irrigation (G_{Is}, GI_g), surface withdrawals ($S_{w,}$), Irrigation Water Footprint index ($I_{w(s)}$ and $I_{w(g)}$).

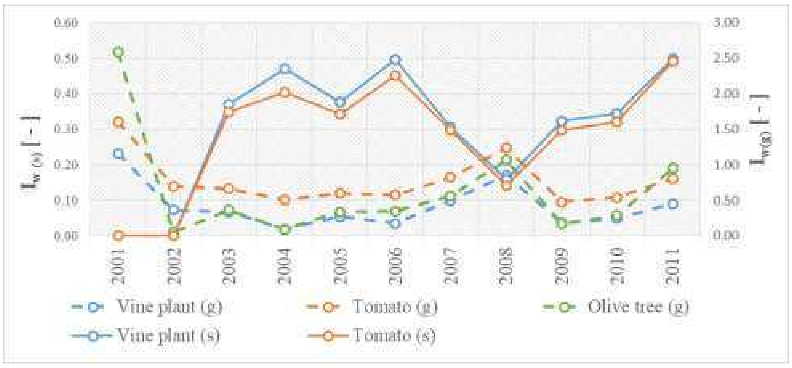


Figure *22:* Irrigation Water Footprint Index during 2001-2011, for processing tomatoes (orange lines), vine plants (blue lines) and olive trees (green lines). The dashed lines identify the results of the Irrigation Water Footprint index related to groundwater abstraction ($I_{w(g)}$)), whereas the continuous one the results of irrigation water footprint index related to surface water abstraction ($I_{w(s)}$).

4.2.2.2 Energy Footprint for Irrigation Index

The economic land productivity has been calculated for each crop, confirming that the olive orchards are the less profitable, with an economic land productivity of 1,211 €/ha; on the other hand, vineyards are the most profitable (≈7,905 €/ha), being the E_{lp} of processing tomato approximately equal to 6,400 €/ha.

In terms of energy requirements, due to the system' characteristics, $I_{en(g)}$ *is* the unique component of the indicator. The values for vineyards are half of those for tomato (Table 8), whereas, the energy consumption for olive trees is significantly lower ($E_{a(g)}$ ≈340 kWh/ha). The Energy Footprint for Irrigation Index $I_{en(g)}$ values, calculated according to Eq (10), are in Figure 23. Having as reference the groundwater withdrawals, the olive tree cultivation has the highest average value of the index (≈ 0.29 kWh/€), which is comparable with the processing tomato one (≈0.24 kWh/€) and significantly higher than vineyard one (≈0.10 kWh/€). The results are summarized in Table 8.

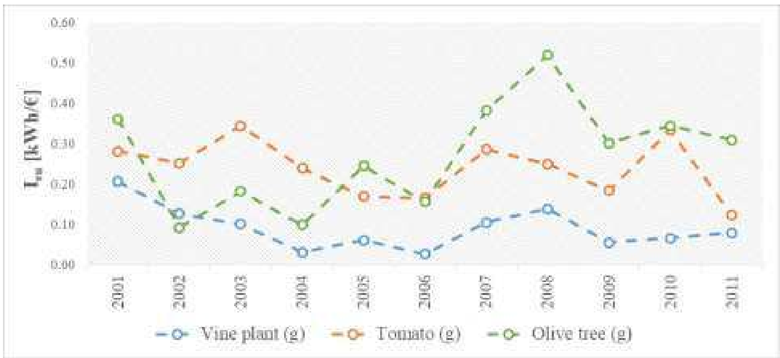


Figure 23: Values of Energy Footprint for Irrigation Index. The values of the Energy Footprint for Irrigation Index I_{en} are plotted for each crop over the entire period (2001-2011) associated to groundwater withdrawals $I_{en(g)}$

CROP	**$E_{a(g)}$ [kWh/ha]**	**E_{lp} [€/ha]**	**$I_{en(s)}$ [kWh/€]**	**$I_{en(g)}$ [kWh/€]**
Olive	339.52	1,211.93	**-**	**0.29**
Vine	737.88	7,905.52	**-**	**0.24**
Tomato	1477.95	6,434.98	**-**	**0.10**

Table 8: Summary of average values for the unit Energy Consumption Index, Economic Land Productivity and the Energy Footprint Index for the investigated crops

4.2.2.3 Irrigation Water-Cost Footprint Index

The analysis of the irrigation water cost, referring to both water sources showed as, tomato and vineyards, have comparable surface water cost ($C_{w(s)}$ values respectively equal to 171.50 €/ha and 171.66 €/ha), while very different results were obtained in terms of groundwater costs; the water cost for processing tomato is more than half of that for vineyard (i.e., values of 321.9 €/ha and of 148.17 €/ha respectively). The groundwater cost was computed for olive orchards, showing the lowest value (≈73.95 €/ha). The $I_{e(s)}$ and $I_{e(g)}$, data according to the Eqs. (12) – (13), are in Figure 24. The production of vineyard is associated with lower values of the index, being it characterized by higher economic profitability, both in terms of surface water and groundwater. Conversely, olive trees present a high average value of the $I_{e(g)}$ (approximately 0.06) due to their limited economic profitability. At the end, the processing tomato show intermediate values of the index (table 9). The results of the irrigation water-cost footprint also show that, for a fixed crop, the values of $I_{e(g)}$ are significantly higher than those of $I_{e(s)}$. This is due to the assumption to consider only the minimum water supply (i.e., 2050 m^3/ha) withdrawn from irrigation consortium. Table 9 summarizes these results

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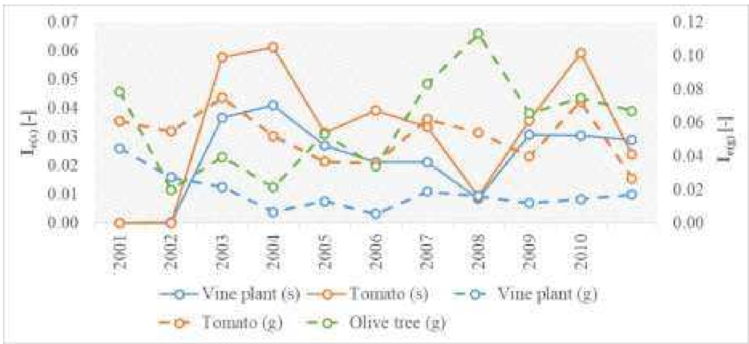

Figure *24*: Values of the Water Cost Footprint Index. The values of Ie are plotted for each crop over the entire period (2001 - 2011). Both the values associated to surface Ie(s) and groundwater withdrawals Ie(g) are plotted, with continuous and dashed lines respectively.

CROP	**$C_{w(s)}$ [€/ha]**	**$C_{w(g)}$ [€/ha]**	**$I_{e(s)}$ [-]**	**$I_{e(g)}$ [-]**
Olive	-	73.95	**-**	**0.06**
Vine	171.66	148.57	**0.02**	**0.02**
Tomato	171.50	321.90	**0.11**	**0.01**

Table 9: Summary of average values of unit water cost and Water-Cost Footprint Index for the investigated crops.

4.2.2.4 Comparative analysis of the indices assessing irrigation sustainability and related impacts

In analogous with the Alimini Piccolo case, a comparative analysis has been carried out considering two approaches: i) a comparison in a disaggregated form, considering the two water sources (Figure 25), to identify which is preferred and the implications of such a choice in economic and energy terms; and ii) a comparison using a hybrid version of the indices (Figure 26) for highlighting the benefits and the impacts originated by the cultivation of different crops, considering the combined use of the two water sources. The results of these analyses are plotted on a spider-graph in which, for a better visualization, the normalized index are plotted in logarithmic scale. Also in this case, the normalization has been made with respect to the relative maximum values (see appendix C). In more detail, the olive production has the highest environmental implications in terms of groundwater exploitation (I_w= 0.62), whereas the low profitability (E_{lp} ≈1,211 €/ha) negatively influences asthe water-cost footprint index as the energy footprint index. On the other hand, tomato production requires a large volume of water mainly deriving from groundwater abstraction ($I_{w(s)}$ = 0.28; $I_{w(g)}$ = 0.78); moreover, it present the higher energy and economic impacts due to the higher cost of water compared with the economic crop value (E_{lp} ≈ 6400 €/ha). With reference to the grapevine, it has lower impacts in term of water consumption ($I_{w(s)}$ = 0,30; $I_{w(g)}$ = 0.42) and it represents the most profitable production, due to the high economic value of this crop (E_{lp} ≈ 7900 €/ha). Thus, although the energy consumption and the cost of water are highly relevant, they might be considered ‘sustainable' due to their profitability.

The same conclusions are supported by a ‘hybrid' version of the indices (figure 26), calculated considering the ratio between surface and groundwater volumes used for crop production. Starting from which, different profiles of the investigated crops can be identified and described within the WEFN framework. The processing tomato crop profile is characterized by the highest value of I_w (1.06) and moderate values of I_{en} (0.18) compared with the other two crops; the same for the I_e (0.05) values. These values are the effect of high irrigation requirements, which are "balanced" in terms of energy consumption and water costs by the high land productivity. Considering the vineyards, it present a moderate impacts in term of water consumption I_w (0.78), along with the lowest impacts in terms of economic cost/benefit (I_e 0.03) and energy consumption values of I_{en} (0.7). This is an effect of medium-high irrigation requirements and an high economic land productivity. On the contrary, the olive grove profile is associated to lowest I_w values (0.62), and the highest values of I_{en} (0.27) and I_e (0.06). These results confirm those obtained in Alimini Piccolo case. Indeed, also in this case the olive groves appear as the most sustainable production due to their low irrigation requirement and water-stress tolerance, though the low land productivity corresponds to high energy and water cost indices.

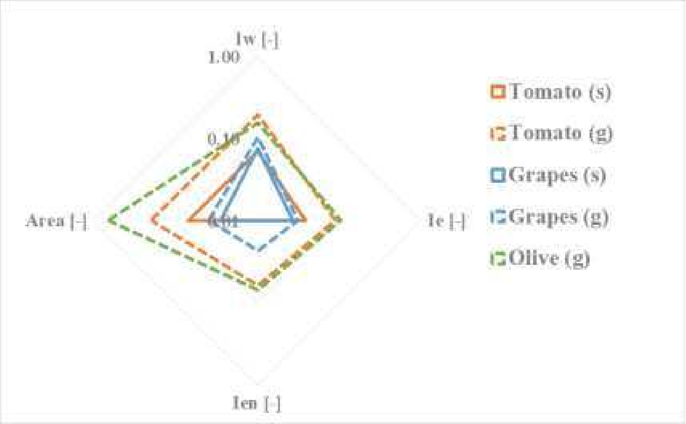

Figure *25*: Footprint index-based approach for WEFN assessment of agricultural production. The graph includes the logarithmic values of normalized index. Dashed lines refer to groundwater withdrawals, while continuous lines refer to surface water.

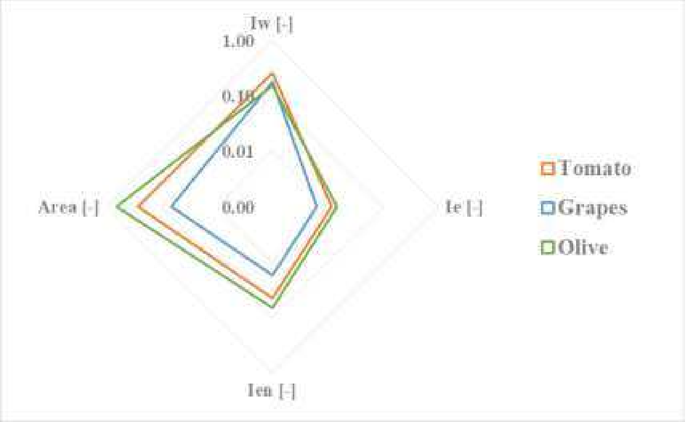

Figure *26*: Footprint index-based approach for WEFN assessment of agricultural production. The graph includes the logarithmic values of normalized index referring to the hybrid version of the comparative analysis

Comparative analysis hybrid version				
CROP	**I_W [-]**	**I_{en} [kWh/€]**	**I_e [-]**	**AREA [ha]**
Vine plant	*0.72*	*0.10*	*0.03*	*6400*
Tomato	*1.06*	*0.06*	*0.05*	*22000*
Olive tree	*0.62*	*0.13*	*0.06*	*55000*

Table 10: Summary of average values of the comparative analysis hybrid version

CHAPTER 5
SCENARIO ANALYSIS

"We've all got both light and dark inside us.
What matters is the part we choose to act on.
That's who we really are"

J.K. Rowling,
Harry Potter and the Order of the Phoenix

This chapter aims to evaluate the effects on irrigation water management system due to the implementation of a given sustainability policy. In doing so, the effects on the system associated with five different scenario related to plausible sustainability policies implementation are analysed. Usually, a scenario is a description of possible events that might reasonably take place (Jarke, Bui and Carroll, 1998). As per Jarke, Bui and Carroll, (1998) developing scenarios aims to stimulate thinking about occurrences, assumptions relating these occurrences, possible opportunities and risks, and courses of action. Therefore, scenario analysis is not intended at obtaining forecasts rather than to advocate the creation of alternative images of the future development of the external environment (Postma and Liebl, 2005). Various approaches for constructing scenarios can be found in the literature ranging from an informal imaginative exercise by a single individual to a systematic group process (Postma and Liebl, 2005). However, the building scenario activity is not the purpose of the present chapter, rather than it aims at analysing the effects of different alternatives to the sustainability policy though the integration of system analysis and indicator-based approach.

The policy alternatives supporting the scenarios were generated by local stakeholders (i.e., Consorzio di Bonifica della Capitanata, Regional authority and Farmers) during the "Design of Policy Alternatives Workshop" organized by LAMSADE-CNRS (Laboratory for Analysis and Modelling Systems for Aid to Decision - National Research Council) of the University Paris-Dauphine (France) in collaboration with IRSA-CNR (Water Research Institute – National Research Council) of Bari (Italy) and CSC (Centre de Gestion Scientifique), Ecole des Mines de Paris (France), in January 23rd 2017.

The workshop aimed to design innovative public policies for supporting the sustainable management of water resources in Capitanata involving local community. During the workshop discussions, several policy alternatives were generated. The five more significant alternatives were used as starting point to developed the following scenarios. The main features of the selected policy alternatives are explained in detail in the next and briefly summarized as follows:

- Integrated management of water resources considering the Consorzio di Bonifica della Caitanata as a public authority responsible for the management of both surface and groundwater resources (see section 5.2);
- Increasing surface water availability by using other regional sources considering the Piano dei Limiti dam, which is a new dam planned to be building Consorzio di Bonifica della (see section 5.3);
- Artificial groundwater recharge to reduce the effects of irrigation practice on this source, considering the outflow volume of the Occhito reservoir directly infiltrated in the existing pumping wells feasibly connected to the irrigation network (see section 5.4);

- Efficient irrigation system considering the sub irrigation as the most efficient irrigation approach (see section 5.5);
- Reuse water (see section 5.6).

With the end of comparing the above scenario with a base line, the current scenario related to an average year is analysed and the results are reported in section 5.1.

5.1 Current scenario

The current scenario has been developed considering the collected data and by implementing the proposed methodology with reference to an mean year characterizing by an annual precipitation, calculated using historical data (1969 - 2011), equal to 558 mm and a distributed water volume equal to 77,12 Mm^3.

Figure 27 shows the scenario results confirming the previous findings; numerical values are in Table 11. The current scenario confirms that the olive production presents the highest environmental implications in terms of groundwater exploitation (I_w= 0.42), along with highest values of water-cost and the energy footprint indexes (i.e., I_e = 0.04 and $I_{en.}$=0.28); processing tomato requires instead a large volume of water mainly deriving from groundwater abstraction ($I_{w(s)}$ = 0.42; $I_{w(g)}$ = 0.58), but has the higher energy and economic impacts due to the higher cost of water compared with the economic crop value (i.e., $I_{e(s)}$ = 0.04 and $I_{en(s)}$=0 while , $I_{e(g)}$ = 0.03 and $I_{en(g)}$=0.17). The grapevine production has lower impacts in term of water consumption ($I_{w(s)}$ = 0,30; $I_{w(g)}$ = 0.14) along moderate values of water-cost and the energy footprint indexes (i.e., $I_{e(s)}$ = 0.02 and $I_{en(s)}$=0 while , $I_{e(g)}$ = 0.01 and $I_{en(g)}$.=0.04).

Moving from these results, the effects on the system related to the implementation of plausible sustainability policy are analysed.

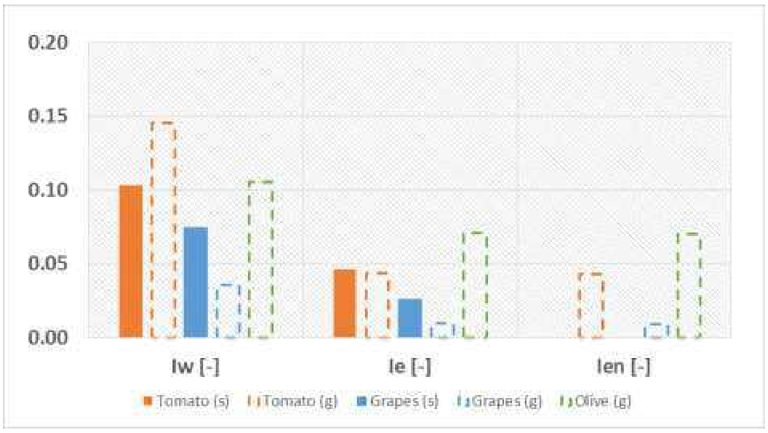

Figure 27: Footprint index-based approach for WEFN assessment of agricultural production. The graph includes the normalized index referring to current scenario.

CROP	Iw [-]	Ie [-]	Ien [Kwh/ha]
Tomato (s)	0.42	0.04	0.00
Tomato (g)	0.58	0.03	0.17
Grapes (s)	0.30	0.02	0.00
Grapes (g)	0.14	0.01	0.04
Olive (g)	0.42	0.04	0.28

Table 11: Summary of the current scenario results

5.2 Integrated water management resources (i.e., surface and ground water resources)

Groundwater is a resource widely diffused in the Capitanata area with several uncontrolled accesses. For the above reasons, according with Giordano, Brugnach and Pluchinotta, (2016), groundwater is typically perceived as a private resource not managed by a public entity. For promoting an alternative to the uncontrolled groundwater abstractions, during the workshop discussion local community proposed a groundwater management by single entity, with legitimacy for decisions and actions. In particular, as emerged from workshop discussion, this scenario provides for the Consortium as public management authority of integrated water resource related to both surface and ground water.

The benefit of implementing this policy is related to a greater control of the abstracted groundwater, but it requires to define a regulation criteria for groundwater management.; more in deep, a careful management of groundwater resources requires increasing management cost for water agency (e.g., energy cost, maintenance cost, water meters installation cost, etc.). Therefore, implementing this policy assuming needs to an economic regulation by defining a groundwater tariff able to include these supplementary costs. In this view, for evaluating the effects on the system, a groundwater tariff equal to 0,12 €/m^3 has been assumed considering the percentage of water volume abstracted from each source as a constant. This implies to consider the groundwater tariff equal to the economic contribution of the minimum water supply (i.e., 2050 m^3/ha) for surface abstraction. Figure 28 summarizes the main results obtained from the implementation of the indicator-based approach. Undoubtedly, a regulation of groundwater entails an increase of groundwater cost, resulting in raising the water-cost index related to groundwater abstraction, which approximately redoubled the indicator values of the current scenario (Figure 29). Considering the system’s dynamic (see Figure 15), increasing groundwater cost (i.e., GW cost in the map) results in decreasing farmer’s profit (i.e., expected farm profit in the map). Consequently, a plausible implication of this policy is related to a decreasing irrigated area (i.e., irrigated area in the map)

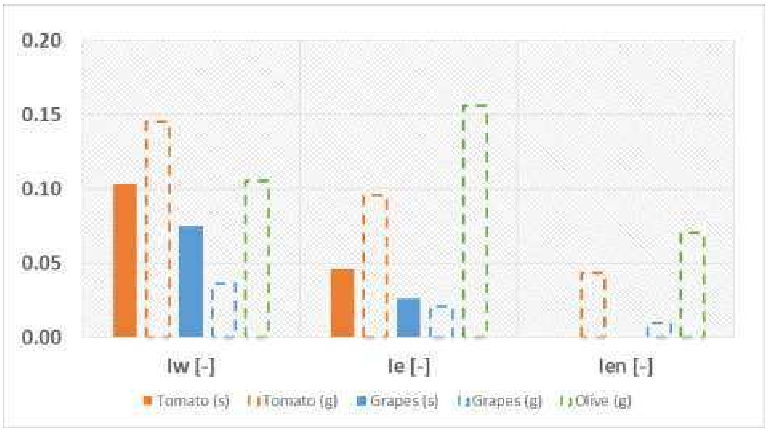

Figure 28: Footprint index-based approach for WEFN assessment of agricultural production. The graph includes the normalized index referring to the Consorzio di Bonifica di Capitanata as management authority of integrated water resources (i.e., surface and ground water resources) scenario.

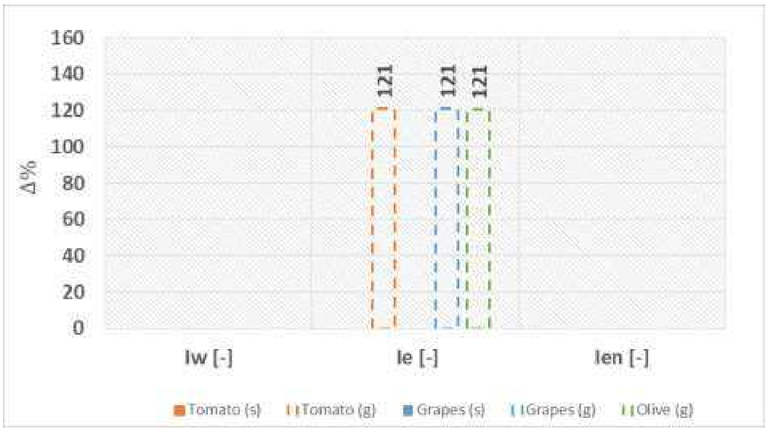

Figure 29: Footprint index-based approach for WEFN assessment of agricultural production. Percentage variation of the proposed scenario calculated with respect to the current scenario.

5.3 Increasing surface water availability by using other region sources scenario

The main factor conditioning groundwater exploitation in the studied region is related to the limited surface water availability. For decreasing the impacts on groundwater source, during the workshop, another important alternative is specifically related to increasing water availability. This scenario results in building new infrastructures (i.e., dams); the idea is to take into account a construction of a new dam called "Piano dei Limiti" in Fortore watershed. In order to evaluate the impacts associated with the implementation of this hypothesis, the scenario was developed assuming an increase of surface waters equal to the maximum capacity of Piano dei Limiti dam (i.e., 40 Mm^3). In addition, a water tariff policy equal to the actual water-pricing scheme was assumed. Figure 30 shows the results of indicator-based approach implementation. in which it appears clear that this policy brings in decreasing the impacts on groundwater resources (i.e., $I_{w(g)}$ decreases of approximately 55%) as shown by Figure 30, and in decreasing the consumed energy (i.e., $I_{en(g)}$ approximately decreases of 40%). Nevertheless the results highlight also a quick rise of water cost related to surface water abstraction (i.e., $I_{e(s)}$ increases of 42%). Comparing these results with the dynamic of the investigated system (see Figure 15) an increase in surface water cost (i.e., Irrigation water cost in the map) results in decreasing withdrawals from consortium (i.e., water distributed by water management authority in the map) and accordingly a groundwater withdrawal (i.e., GW use in the map) intensification. On the other hand, enlarging the available amount of surface water influences the amount of water available for farmers (i.e., Irrigation budget in the map) and this may results in increasing irrigated area with cascading impacts on groundwater resource. Therefore, the plausible implementation of this policy without any regulation of groundwater withdrawals may results beneficial to address water scarcity issues, but on the other hand, it may be ineffective to prevent groundwater exploitation.

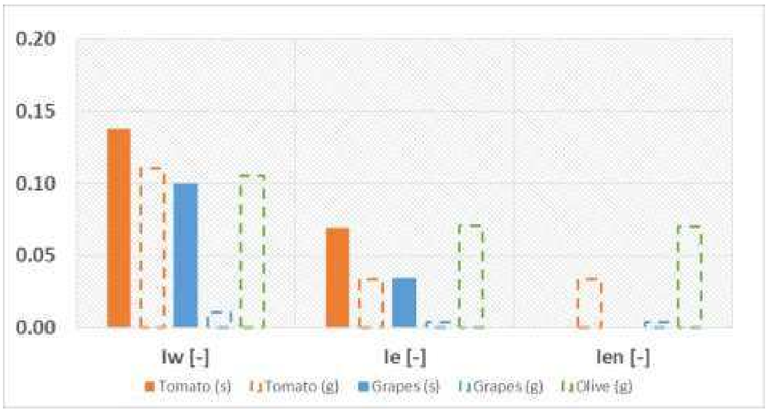

Figure 30: Footprint index-based approach for WEFN assessment of agricultural production. The graph includes the normalized index referring to the scenario related to increasing surface water availability by using source of other regions.

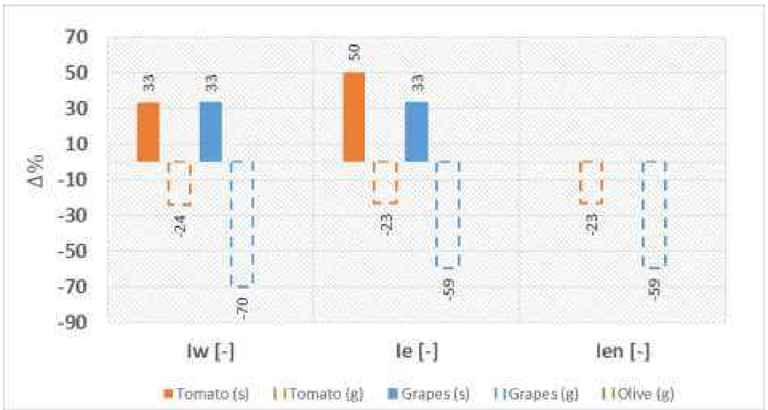

Figure *31:* Footprint index-based approach for WEFN assessment of agricultural production. Percentage variation of the proposed scenario calculated with respect to the current scenario.

5.4 Artificial groundwater recharge scenario

An alternative proposed by local community during the workshop is related to increasing groundwater volume by artificial recharge; this scenario offers a series of technological solutions to improve groundwater quality, especially for the groundwater sources located in the coastal zone. The implementation of this scenario requires a series of legislative and technical issues (i.e., chemical parameters of the water used for the recharge) that are not investigated in detail. Guyennon *et al.*, (2017) proposed a managed aquifer recharge (MAR) scenario in Capitanata consortium.area in which an average volume of water that can be infiltrated in groundwater equal to 14 Mm^3 was estimated (Guyennon *et al.*, 2017). Staring from these considerations, the indicator based approach has been implemented in study area in order to evaluate the effects of the policy implementation and the results plotted in Figure 32. The main effect related to the implementation of this policy is related to a decreasing impacts on groundwater whereas it does not have any implication on the amount of abstracted water from a specific source.

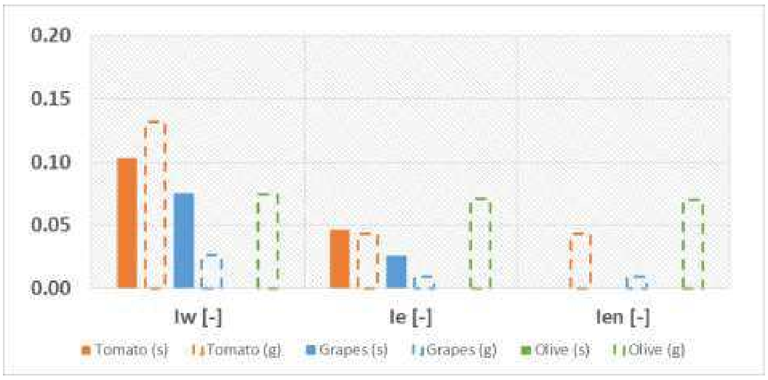

Figure 32: Footprint index-based approach for WEFN assessment of agricultural production. The graph includes the normalized index referring to the scenario related to artificial groundwater recharge.

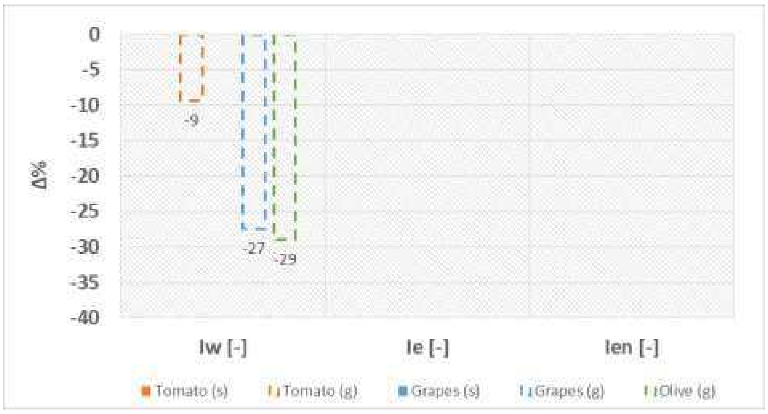

Figure 33: Footprint index-based approach for WEFN assessment of agricultural production. Percentage variation of the proposed scenario calculated with respect to the current scenario.

5.5 *Efficient irrigation system scenario*

A complementary scenario, coming out from the conclusions of the workshop discussion, is in implementing a more efficient irrigation technologies aimed to optimize the irrigation by reducing water losses. The analysis of the irrigation practice in Capitanata demonstrated that the most diffused irrigation techniques are sprinkler and drip irrigations, which in Fortore district respectively cover 27% and 59% of the irrigated area (ISTAT, 2000). The two different techniques are characterized by a mean irrigation efficiency respectively equal to 70% and 90%. Therefore, for evaluating the effects of an investment in a more efficient irrigation technologies, a sub-surface irrigation is considered. .The main advantage is in the efficiency, although it is worth to note that irrigation efficiency not only depends on the irrigation system itself, but also on its design, installation and management (Payero *et al.*, 2005). Consequently, only if designed, installed and managed correctly subsurface irrigation can be more efficient than any other irrigation system. In our case, the efficiency depends on installation layout, since the driplines are usually installed in the soil between every other crop row and, accordingly, the system only wets a fraction of the soil in the root zone reducing the net irrigation requirement. Moreover, due to the burial pipelines, no irrigation water is lost due to evaporation and runoff, since the surface soil remain dry (Payero *et al.*, 2005). On the other hand, the main disadvantage is related to the high installation cost compared with other techniques. In order to evaluate the effects of a new investment in sub-surface irrigation, an theoretical efficiency equal to 100% has been considered. In addition, as derived by Payero *et al.*, (2005), a capital installation cost equal to 4293,4 €/ha including the maintenance cost (i.e., 143,6 €/ha per year) and an useful lifetime equal to 10 years. More, for estimating the plausible layout of the system associated with the considered crops, the following cost has been assumed:

- 430 €/ha per year for processing tomato considering the full cost of investment and maintenance;
- 288 €/ha per year for grapes considering 2/3 of the full cost;
- 142 €/ha per year for olive trees considering 1/3 of the full cost.

In order to consider the implication of the investment on the withdrawals from a specific source, the above costs have been shared for each source considering the actual ratio of abstraction. Figure 35 shows the obtained results in which a mean value of water saving is about 20% (Figure 36). The overall water cost increase is approximately equal to 200% if compared with the groundwater withdrawals, while in case of surface withdrawals the water cost rises about 74%. Consequently, as in the integrated water management scenario, considering the system dynamic (Figure 15), a plausible implication of this policy is a decreasing irrigated area.

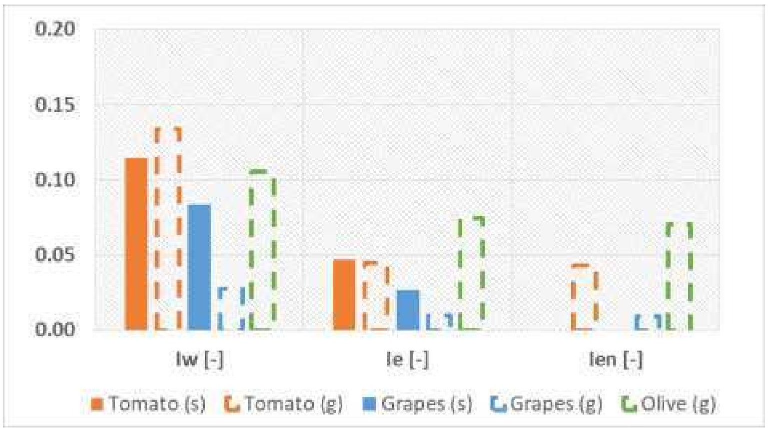

Figure *34:* Footprint index-based approach for WEFN assessment of agricultural production. The graph includes the normalized index referring to the investment in more efficient irrigation system scenario.

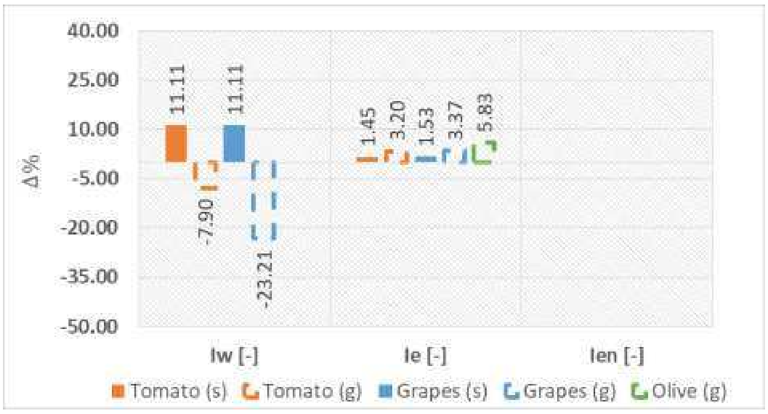

Figure *35:* Footprint index-based approach for WEFN assessment of agricultural production. Percentage variation of the proposed scenario calculated with respect to the current scenario.

5.6 Reuse water scenario

Local community proposed the use of reused water in order to reduce the impacts on groundwater sources. It is, indeed, widely agreed that the effluent reuse leads to increase the water supply from unconventional sources and theoretically reduces the exploitation of surface and groundwater (Arborea *et al.*, 2017).

Since the beginning of the 80s, the Puglia Region has planned the execution of a series of water infrastructures aimed at completing the urban sewerage networks and wastewater treatment with the end of making available large amount of treated water.

In 1993, for increasing the water availability for agricultural purposes, the wastewater treatment plants of Cerignola and Margherita di Savoia were equipped for distributing treated waters through public irrigation networks. After this, the need to find alternative water sources emerged with evidence during the 2000-2002 drought period. Wastewater can only be reused if the physical, chemical and biological characteristics are consistent with those required by the Italian regulations (D.L.152/06 and D.M.185/2003). For evaluating the effects of reusing wastewater, a scenario in which a capacity equal to 175,000 equivalent inhabitants has been considered (i.e., Foggia WWT availability).

The potential water volume to be used in agriculture and related energy consumption for the treatment were derived from the results obtained by Arborea *et al.*, (2017), which assessed the real economic benefits of reclaimed wastewater as a productive factor for irrigation. Specifically, in the above cited paper, the "additional" processes of tertiary treatments necessary for reusing the effluent in agriculture without taking into account the capital and management costs was considered. With reference to the Italian law that establish the effluent standard quality requirements for surface water discharge (T1), ground surface discharge (T2), and reuse (T3), the authors evaluated the additional treatment and related costs needed to reach T3 quality values in two different hypothesis related to:

- Effluent with standard quality values equal to T1
- Effluent with standard quality values equal to T2

even if in this work only the T1 scenario was considered. As Arborea *et al.*, (2017), an average water flow equal to 5940 m^3/day and an average potential reused water volume equal to 7.93 Mm^3 were assumed; in addition an energy cost equal to 112,968.5 € per year was associated to the additional treatments, resulting in 0.14 kWh/m^3 of consumed energy assuming an energy tariff equal to 0.1 €/kWh. Taking into account also transportation, storing and pressurizing cost for distributing water at farm gate, an energy consumption equal to 1.09 kWh/m^3 has been estimated. Figure 36 shows the results obtained from the application of the implemented methodology. The beneficial effects (Figure 37) are related to a decreasing impacts on groundwater source (i.e., $I_{w(g)}$ is about -10%), with cascading impacts on the water cost, which on average $I_{e(g)}$ values reduced of 8%. On the other hand, additional energy consumption occurs (i.e., $I_{e(re)}$ equal to 0.023 and 0.013 respectively for processing tomato and grapes). Considering the system dynamic (Figure 15), the implementation of this scenario results in increasing surface available water that influence the variable irrigation budget; hence, a rising of irrigated area may result from the increment of irrigation budget.

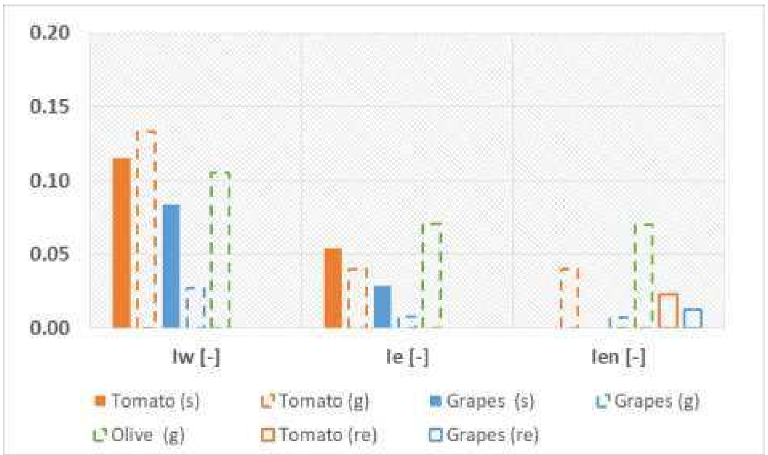

Figure 36: Footprint index-based approach for WEFN assessment of agricultural production. The graph includes the normalized index referring to the reuse water scenario.

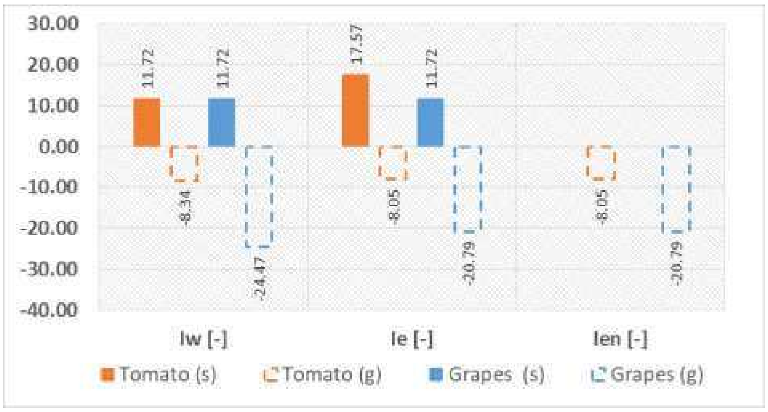

Figure 37: Footprint index-based approach for WEFN assessment of agricultural production. Percentage variation of the proposed scenario calculated with respect to the current scenario.

CONCLUSION

> *"You cannot hope to build a better world without improving the individuals. To that end, each of us must work for his own improvement and, at the same time, share a general responsibility for all humanity, our particular duty being to aid those to whom we think we can be most useful"*
>
> *Marie Curie*

The implemented methodology aims to evaluate the multi-dimensional implications of irrigation water use at local scale by identifying the main factors controlling the selection and exploitation of water sources within the WEFN framework. Specifically, a conceptual model has been developed in order to analyze the dynamic of a given irrigation system. It helped in understanding which are the main elements influencing the sustainable management of water resource. The obtained results are in line with the findings of Giordano, Brugnach and Pluchinotta, (2016) , according to which a dense network of relationship among different decisional actors involved strongly influence the dynamic of the system, whose behavior mainly depends by external drivers (e.g., economic land productivity and water availability) and by the behavior of others. Particularly, system analysis helps in drawing several general conclusions, highly relevant in supporting sustainable management of water resource for irrigation purposes. Firstly, a direct connection between farmers' revenue and water source selection, cost and consumption has been highlighted; secondly, the crop selection is mainly driven by economic land productivity and, similarly, the selection of the water source for irrigation is strongly conditioned by the water (and energy) cost (Smidt et al., 2016; Zingaro et al., 2017, b). Referring specifically to the case study, the surface agency, whereas the groundwater source is generally cheaper, highly affordable and freely accessible (Giordano et al. 2015; Zingaro et al. 2017, a), although sometimes energy-intensive (Ringler and Lawford, 2013).

These findings were then used to define three different indices capable to quantitatively evaluate the sustainability of irrigation water system considering the multi-dimensional implication of water use. Indeed, an essential element for the definition of sustainability indicator consists in identifying and characterizing the physical and social boundary of the system (Giupponi, Gain and D'Odorico, 2015). Therefore, an index-based approach was implemented through different crops that have been directly compared to estimate the main impacts of the dynamic previously analyzed. The index-based approach is proved to be reliable enough for the quantitative assessment of irrigation water sustainability, which could be highly useful for decision-makers. Several studies analyzed WEFN holistically, introducing a composite index based on the integration of different sub-indices related to water, food, and energy (e.g., Moioli et al., 2016; Willis et al., 2016). On the one hand, the adoption of a global index has the main advantage of providing a synthetic assessment of the multiple dimensions of the nexus, which are tightly interconnected, supporting a global sustainability assessment. Such an aggregated form, could mainly support assessing the global impacts of irrigation practice over the entire area under investigation. Moreover, the analysis of sub-indices, specifically focused on individual aspects of the nexus, helps better note the root causes of unsustainability at the local level and investigate more in depth the main cross-sectorial dynamics, thus supporting the identification of the most suitable strategies to drive the transition process towards sustainability. Going into further details, the three introduced indices can be further disaggregated, to analyze separately the use of multiple water sources (only surface and ground waters have been considered, but the methodology could be easily adapted to alternative water sources). Although the use of multiple indices could result in additional analysis complexity, it helps in identifying more directly the impacts and benefits associated to the use of specific water sources, taking into account the main differences between irrigation supply systems (e.g., efficiency, management practices, operation, cost, etc.). Furthermore, the adopted integrated approach helps in analyzing the link between water and energy for irrigation. This element of the nexus is particularly crucial since both resources are decreasing and have significant mutual influences (Ringler, Bhaduri and Lawford, 2013). Energy costs for pumping and supply, expressed by I_e, can have a different impact on the whole system, which should be mainly related to the amount of water required for each crop and the final revenue of farmers. The integration among qualitative aspects of water use (i.e., system analysis) and the quantitative aspects of irrigation practices (i.e., indicator-based approached) has shown to be indispensable for supporting decision making of sustainable management of water resource allowing also to evaluate the effects on the system associated with a given sustainability policy. Indeed, as resulted from the scenario analysis, the integration of the two approaches allowed to evaluate the effectiveness of the plausible implementation of the policy suggested by local community. The obtained results of the scenario analysis highlight that although the proposed policies have positive environmental impacts on the short time, they may fail in the long term due to dynamic mechanisms that depend on the behaviour and interests of the actors involved.

Although the methodology does not require complex modeling, its implementation might be limited by data availability (e.g. reliable estimates of surface and groundwater withdrawals, cultivated areas and crop yields, efficiencies), which should be guaranteed by extensive monitoring activities. To appreciate the replicability of the proposed methodology and investigate potential drawbacks and limitations in different contexts, the approach was implemented in two different case studies. The main differences between the case studies are related to: i) scale analysis ii) different crop water requirement; iii) the presence of gravity surface water supply systems; iv) a different water tariff scheme based on different price thresholds for block volumes of water; and v) different cost and accessibility of groundwater. Despite such differences, the methodology is robust enough to be adopted in a different framework. It is also worth noting that the main advantage of the methodology relies in its simplicity, directly depending on the identification and analysis of a few key quantitative elements.

Although the results of the participatory workshop (described in appendix E) are still being analyzed few general conclusion can be summarized following. Firstly, the workshop discussion confirmed that the integration among qualitative aspects of water use (i.e., system analysis) and the quantitative aspects of irrigation practices (i.e., indicator-based approached) is indispensable for evaluating the effectiveness of a given sustainability policy especially at the mid-long time. Indeed, as resulted from the discussion the indicator can orient decision making of sustainable management of water resources only in the short time. Whereas the mid-long time evaluation requires a careful knowledge of the system behaviour. Secondly, as resulted from the workshop discussion, the indicator in this state of the implemented methodology are not enough to capture the whole complexity of a given irrigation system. Indeed, the role of several drivers and the issues related to a comprehensive sustainability assessment are currently neglected (e.g., the analyses are only limited to irrigation practices and do not consider other agricultural practices). Lastly, it was revealed that the CLD is not able enough to capture the different decision-making scales at which actors involved operate. For the above reasons future development are related to i) define additional indicators capable to capture the whole complexity of the system; ii) resolving the problem of representing different decision-making scale in a unique diagram to describe the system behavior. Getting further insight into these issues is an essential element for a comprehensive assessment and for supporting effective decision-making towards more sustainable irrigation water use.

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Appendix A: Summary of the variable included in CLD of system dynamic

VARIABLE	DESCRIPTION	FUNCTION (i.e. relation in CLD)
ATTRACTIVENESS OF PROFITABLE CROP	Attraction of farmers to more profitable crops	=f (Expected farm profit, Irrigation budget)
CROP MARKET PRICE	Agricultural wholesale selling price of agricultural product	Dato input (Camera di Commercio Foggia)
CROP WATER REQUIREMENT	-	Dato input (ricavato dal software CropWat)
DURATION OF IRRIGATION SEASON	Irrigation season duration established by the Capitanata Land Reclamation Consortium	=f(water demand from water management authority)
ECONOMIC LAND PRODUCTIVITY		=f(Crop market price, Yield)
ENERGY TARIFF		Dato input (Enel tariffa di tipo industrial)
EXPECTED FARM PROFIT		
GW COST	Groundwater withdrawals cost	=f(GWuse, GWlevel, Energy tariff)
GW EFFICIENCY	Water efficiency related to groundwater abstraction	
GW LEVEL	Groundwater table	=f(GW use)
GW QUALITY	Groundwater quality	=f(GW level)
GW USE	Water volume abstracted from groundwater	=f(Limit to use GW, Search of alternative water source)
GWF BLUE	Componente blue del water footprint relativa al prelievo da fonte sotterranea	=f (GW efficiency, GWuse)
$I_{E(G)}$	Irrigation water cost footprint index	=f(economic land productivity, GWcost)
$I_{E(S)}$	Irrigation water cost footprint index del prelievo dal Consorzio di Bonifica della Capitanata	=f(economic land productivity, Irrigation water cost related to water management authority)

$I_{EN(G)}$	Energy footprint for irrigation index del prelievo da falda	=f(Economic land productivity, GW level, pump efficiency)
IRRIGATED AREA	-	=f(Attractiveness of profitable crops)
IRRIGATION BUDGET	Irrigation Water volume available for farmers as difference between irrigation requirement and water supply	=f(Irrigation water requirement, water supply)
IRRIGATION WATER COST	Water cost related to water abstraction from consortium	=f(Water tariff, water distributed by water management authority)
IRRIGATION WATER COST RATIO	Ratio between irrigation water cost and groundwater cost	=f(Irrigation water cost, GW cost)
IRRIGATION WATER REQUIREMENT	-	=f(crop water requirement, precipitation)
$I_{W\ (G)}$		=f(GWF blue, WFgreen, P)
$I_{W\ (S)}$		=f(SWF blue, WFgreen, P)
LIMIT TO USE GW	Percentage of groundwater abstraction established by Regional Authority	=f(GW quality)
PRECIPITATION	-	-
PUMP EFFICIENCY	-	-
SEARCH OF ALTERNATIVE WATER SOURCE	Farmers' tendency to search for alterative water sources	=f (Irrigation water cost ratio, water supply
SW EFFICIENCY	Water efficiency related to consortium abstraction	-
SWF BLUE	Water Footprint Blue	= f(SW efficiency, Water distributed by water management authority)
WATER AVAILABILITY FOR WATER MANAGEMENT AUTHORITY	-	=f (precipitation, water stored into reservoir, water demand for other use)
WATER DEMAND FOR OTHER USE	Domestic and industrial demand	-
WATER DEMAND TO WATER MANAGEMENT AUTHORITY	-	=f (irrigation water requirement)

WATER DISTRIBUTED BY WATER MANAGEMENT AUTHORITY	-	=f (water demand to water management authority, irrigation water cost)
WATER STORED INTO RESERVOIR	-	=f(precipitation)
WATER SUPPLY	Sum of water distributed by consortium and groundwater use	=f(GW use, Water distributed by water management authority)
WATER TARIFF	-	=f (Duration of irrigation season, Water availability for water management authority)
WF BLUE	Water Footprint blue	=f(Irrigation water requirement, GWF blue, SWF blue)
WF GREEN	Water Footprint green	=f(Irrigation water requirement, GWF blue, SWF blue)
YIELD	Agricultural yield	=f(irrigated area)

Appendix B: CropWat® software and use in the cases studies

1. CropWat® software and use in the cases of Alimini Piccolo Lake

The proposed methodology was implemented in CropWat® software considering the three main crops, in order to estimate irrigation requirements, total gross irrigation and net irrigation activating the irrigation schedule option. Particularly, CropWat ® is a computer programme based on the method described in (Allen, 1998) for the calculation of crop water requirements and irrigation requirements from existing or new climatic and crop data allowing the development of irrigation schedules for different management conditions and the calculation of scheme water supply for varying crop patterns. Data required by software are related to climatic parameters (i.e. precipitation and maxima/minimum temperatures), soil parameters (i.e. total available soil moisture and maximum rain infiltrations rate), crop parameters (i.e. K_c and rooting depth) and irrigation efficiency.

Referring to the case study, monitoring activities allowed estimating the majority of the key parameters used in the methodology. More in detail, daily climate records for the period 2007-2014, deriving from an agro-meteorological station located in Frassanito nearby the lake were used as input. A sandy clay soil and its parameters were derived from the monitoring activities. Therefore, concerning the soil parameters inserted in the software, it was attributed a total available soil moisture of 150 mm/m and maximum rain infiltrations rate of 187 mm/day. Moreover, several interviews with farmers confirmed that sprinkler irrigation method is the most widely diffused technique over the area, and that an irrigation efficiency of about 70% was attributed. Whereas, for what concerns the data related to crop parameters, the FAO database of crop were used.

2. CropWat® software and use in the cases of Capitanata plain

Referring to the Capitanata plain case study, daily climate records for the period 2001-2011, deriving historical series of virtual station estimated through the Thiessen Polygons method, as explained in section 4.2.2. A predominant clay soil and its parameters were derived from the monitoring activities. Therefore, concerning the soil parameters inserted in the software, it was attributed a total available soil moisture of 140 mm/m and maximum rain infiltrations rate of 88 mm/day. Moreover, several interviews with farmers confirmed that drip irrigation method is the most widely diffused technique over the area, and that an irrigation efficiency of about 90% was attributed. Whereas, for what concerns the data related to crop parameters, the CIHEAM-IAMB database was considered.

Appendix C: Threshold values for sustainability indicators

Maximum thresholds values of the sustainability indicators are evaluated in the Puglia Region by implementing the proposed index-based approach considering a hypothetical sustainability and unsustainability conditions. Going into further detail this analysis aimed at evaluating the maximum values of indices and sub-indices in the two distinct conditions. A sustainability condition is the banal case in which agriculture is fed only by precipitation and thus every indicators assume 0 as numerical values.

Conversely, unsustainability situations occurs when the indicators assume the maximum possible values. With the end of evaluating the indices maximum values, the indicator-based approach has been implemented in two distinct scenario respectively related to water abstracted only from surface water source and water abstracted only from groundwater source considering the following assumptions:

- Dry years characterized by annual precipitation equal to 375 mm calculated considering the overshooting probability related to 80 percentile of the historical data of precipitation in the whole region. This assumption results in Irrigation water footprint indices maximization;
- Low economic land productivity for each considered crops. This assumption results in Energy Footprint for Irrigation and Water-cost Footprint Indices maximization;
- Low values of pump efficiency (0.3). This assumption results in Energy Footprint for Irrigation;
- High water table depth (100m). This assumption results in Energy Footprint for Irrigation;

The maximum values obtained by implementing the indicator-based approach are summarize in the following table

Source	I_w [-]	I_e [-]	I_{en} [Kwh/ha]
Surface abstraction	4.02	0.83	4.12
Groundwater abstraction	4.02	0.58	3.92

Appendix D: Summary of the symbols, equations and data requirements in the indices

VARIABLE	*EQUATION*	*DESCRIPTION*	*DATA REQUIREMENTS*
IRRIGATION WATER FOOTPRINT			
AIR [mm]: ACTUAL IRRIGATION REQUIREMENT	-	*Irrigation requirement calculated for each crop under investigation as output of CropWat® software, activating irrigation schedule option*	*Monthly climatic data (i.e. precipitation and maxima and minimum temperatures);* *Crop parameters (i.e. Kc, rooting depth length of cultivation period);* *Soil characteristic (i.e. total available soil moisture and maximum rain infiltration rate)*
$CWU_{blue,i}$ [m^3/ha]: CROP WATER USE BLUE	$CWU_{blue,i} = ET_{blue,i} \times 10$	*Blue water component of the consumptive water use. Calculated for i-th crop*	*ET_{blue} – Amount of water evapotranspirated derived from surface and groundwater source;* *10- Conversion factor from mm to m^3/ha*
$CWU_{green,i}$ [m^3/ha]:	$CWU_{green,i} = ET_{green,i} \times 10$	*Green water component of the consumptive water use. Calculated for i-th crop*	*ET_{green} – Amount of water evapotranspirated derived from precipitation;* *10- Conversion factor from mm to m^3/ha.*

$ET_{a,i}$ [mm]: ACTUAL WATER USE BY CROP	$ET_{a,i} = ET_{blue,i} + ET_{green,i}$	*Evapotranspiration adjustment. Calculated for i-th crop*	*Output of CROPWAT® software (irrigation schedule option).* *See data required for AIR calculation*
$ET_{blue,i}$ [mm]: CROP EVAPOTRANSPIRATION BLUE	$ET_{blue,i} = min(TNI_i; AIR_i)$	*Amount of water evapotraspirated derived from surface and groundwater sources. Calculated for i-th crop*	*TNI_i - Total net irrigation;* *AIR_i – Actual irrigation requirement*
$ET_{green,i}$ [mm]: CROP EVAPOTRANSPIRATION GREEN	$ET_{green,i} = ET_{a,i} - ET_{blue,i}$	*Amount of water evapotraspired derived from precipitation.* *Calculated for i-th crop*	*$ET_{a,i}$ – Actual water use by crop;* *$ET_{blue,i}$ – Crop evapotranspiration blue*
e_c [-]: CONVEYANCE EFFICIENCY	$e_c = \frac{GI_s}{S_w}$	*Conveyance efficiency including evaporation, seepage/leakage, system filling, metered/theft losses related to supply network.*	*GI_s –amount of water distributed to single farm;* *S_w – Amount of water withdrawn from a surface water source;*
e_{farm} [-]: FARM EFFICIENCY	$e_{farm} = \frac{V_d}{GI_s}$	*Efficiency component related to farm management.*	*V_d – Amount of water distributed to the field by farmers;* *GI_s – Amount of water distributed to single farm.*

***e_{app}* [-]: APPLICATION EFFICIENCY**	$e_{app} = \frac{V_{rz}}{V_d}$	*Efficiency component related to irrigation methods.*	V_{rz} *– amount of water stored into the root zone.* V_d *– Amount of water distributed to the field by farmers;*
G_{wi} [m^3]: GROUNDWATER WITHDRAWALS	$G_{w,i} = GI_{g,i}/(e_c \times e_{farm})$	*Amount of water abstracted from groundwater source*	$GI_{g,i}$ *- Amount of water distributed to single farms withdrawn from groundwater source*
GI_i [m^3]: GROSS IRRIGATION	$GI_i = GUI_i \times S_i = GI_{s,i} + GI_{g,i}$	*Amount of water distributed to single farms. Calculated for each crop*	GUI_i *- Amount of water distributed by farms to a unit area;* S_i *- Cultivated area of each crop;*
$GI_{s,i}$ [m^3]: GROSS IRRIGATION ABSTRACTED BY SURFACE WATER SOURCE	-	*Amount of water distributed to farms abstracted from surface water source.*	.
$GI_{g,i}$ [m^3]: GROSS IRRIGATION ABSTRACTED BY GROUNDWATER SOURCE	$GI_{g,i} = GI_i - GI_{s,i}$	*Amount of water distributed to farms abstracted from groundwater source*	GI_i *– Gross irrigation;* $GI_{s,i}$ *- Gross irrigation abstracted by surface water source*
GUI_I [m^3/ha]: TOTAL UNIT GROSS IRRIGATION	$GUI_i = GI_i * 10$	*Amount of water distributed by farms to a unit area.*	GI_i *– Gross irrigation;* *10- Conversion factor from mm to* m^3*/ha;*

GWF$_{blue,i}$ [m^3]: GROUND WATER FOOTPRINT BLUE	$GWF_{blue,i} = WF_{blue,i} - SWF_{blue,i}$	*Groundwater component of the blue water footprint*	*WF$_{blue,i}$ – Water footprint blue* *SWF$_{blue,i}$ - Surface water footprint blue*
I$_{w,i}$ [-]:IRRIGATION WATER FOOTPRINT INDEX	$I_{w,i} = \left(WF_{blue,i}\right)/(P_{i-}\ WF_{green}$	*Impacts of blue water consumption on available rain water resources*	*P$_i$ Annual precipitation distributed to cultivated area;* *WF$_{blue,i}$ – Water footprint blue;* *WF$_{green,i}$ – Water footprint green;*
I$_{w(s),i}$ [-]:IRRIGATION WATER FOOTPRINT INDEX RELATED TO SURFACE ABSTRACTION	$I_{w\ (s),i} = SWF_{blue,i}/(P_i - WF_{gr}$	*Impacts of blue water consumption withdrawn from surface water source on available rain water resources calculated for each crop*	*P$_i$ Annual precipitation distributed to cultivated area;* *SWF$_{blue,i}$ – Surface Water footprint blue;* *WF$_{green,i}$ – Water footprint green;*
I$_{w(g)i}$ [-]:IRRIGATION WATER FOOTPRINT INDEX RELATED TO GROUNDWATER ABSTRACTION	$I_{w\ (g),i} = GWF_{blue,i}/(P_i - WF_{g}$	*Impacts of blue water consumption withdrawn from groundwater on available rain water resources calculated for each crop*	*P$_i$ Annual precipitation distributed to cultivated area;* *GWF$_{blue,i}$ – Groundwater footprint blue;* *WF$_{green,i}$ – Water footprint green;*
S$_i$ [ha]: TOTAL CULTIVATED AREA	-	*Crop cultivated area*	*Data collected from ISTAT for each crop in*

$S_{w,i}$ [m^3]: SURFACE WATER WITHDRAWALS	$S_{w,i} = GI_{s,i}/(e_c \times e_{farm})$	*Amount of water abstracted from surface source Calculated for each crop*	*$GI_{s,i}$ - Gross irrigation abstracted by surface water source;* *e_c –conveyance efficiency;* *e_{farm} – farm efficiency.*
SWF_{blue} [m^3]: SURFACE WATER FOOTPRINT BLUE	$SWF_{blue,i} = S_{w,i} \times e_c \times e_{farm}$	*Amount of water consumed withdrawn from surface sources, calculated for each crop*	*S_w – Amount of water withdrawn from a surface water source;* *e_c –conveyance efficiency;* *e_{farm} – farm efficiency.*
TNI [mm]: TOTAL NET IRRIGATION		*Amount of water distributed by farm to the field, calculated for each crop.*	*Output of CROPWAT® software (irrigation schedule option).* *See data required for AIR calculation*
$WF_{blue,i}$ [m^3]: WATER FOOTPRINT BLUE	$WF_{blue,i} = CWU_{blue,i} \times S_i$	*Blue component of the water footprint calculated for each crop*	*CWU_{blue} – Crop water use blue;* *S_i - Cultivated area of each crop;*
$WF_{green,i}$ [m^3]: WATER FOOTPRINT GREEN	$WF_{green,i} = CWU_{green,i} \times S_i$	*Green component of the water footprint calculated for each crop*	*CWU_{green}– Crop water use green;* *S_i - Cultivated area of each crop;*
ENERGY FOOTPRINT FOR IRRIGATION			
$E_{a(s)}$ [kwh/ha]: UNIT ENERGY REQUIREMENT RELATED TO SURFACE	$E_{a(s),i} = E_{w(s)} \times US_{w,i}$	*Amount of energy required to pump 1m^3 from surface water source to irrigate 1ha*	*$E_{w(s)}$ - Unit energy consumption related to surface water abstraction*

ABSTRACTION			*US_{wi} - volume of water abstracted from surface source to irrigate a unit area (m^3/ha).*
$E_{a(g),i}$ [kwh/ha]: UNIT ENERGY REQUIREMENT RELATED TO SURFACE ABSTRACTION	$E_{a(g),i} = E_{w(g)} \times UG_{w,i}$	*Amount of energy required to pump 1m^3 from groundwater source to irrigate 1ha*	*$E_{w(g)}$ - Unit energy consumption related to groundwater abstraction;* *UG_{wi} - volume of water abstracted from groundwater to irrigate a unit area (m^3/ha).*
E_{lp} [€/ha]: ECONOMIC LAND PRODUCTIVITY	$E_{lp,i} = Y_i \times V_c$	*Unit farmer's revenue*	*Y_i – Crops Yield (Kg/ha)* *V_c - crop market values (€/Kg)*
$E_{w(s)}$ [kwh/m^3]: UNIT ENERGY CONSUMPTION RELATED TO SURFACE WATER ABSTRACTION	$E_{w(s)} = H_{t(s)}/(102 \times \eta_{(s)} \times$	*Amount of energy required to pump a unit volume of water from surface water source.*	*$H_{t(s)}$ – hydraulic head related to surface system.* *η_s – pump efficiency of surface water system*
$E_{w(g)}$ [kwh/m^3]: UNIT ENERGY CONSUMPTION RELATED TO	$E_{w(g)} = H_{t(g)}/(102 \times \eta_{(g)} \times$	*Amount of energy required to pump a unit volume of water from groundwater source*	*$H_{t(g)}$ – hydraulic head related to groundwater system.* *η_s – pump efficiency of groundwater system*

GROUNDWATER ABSTRACTION			
H_t [m]: HYDRAULIC HEAD	$H_t = H_g + H_p + H_e$	*Hydraulic head It was assumed equal to the geodetic altitude H_g*	*H_g – elevation head;* *H_p – head loss;* *H_e - nominal operating pressure of the irrigation system*
$H_{t(s)}$ [m]: HYDRAULIC HEAD RELATED TO THE SURFACE SYSTEM	$H_t = H_g$	*Hydraulic head of surface water system. It was assumed equal to the geodetic altitude H_g (≈30m)*	*H_g – elevation head*
$H_{t(g)}$ [m]: HYDRAULIC HEAD RELATED TO THE GROUNDWATER SYSTEM	$H_t = H_g + H_e$	*Hydraulic head composed only of the elevation head and the nominal operating pressure of the irrigation system*	*H_g – elevation head;* *H_e - nominal operating pressure of the irrigation system*
$I_{en(s)}$ [kwh/€]: ENERGY FOOTPRINT FOR IRRIGATION INDEX RELATE TO SURFACE WATER ABSTRACTION	$I_{en(s)} = E_{a(s)}/E_{lp}$	*Energy requirement from-source-to-field in order to get a unit revenue for the i-th crop. Calculated for each crop*	*$E_{a(s)}$ - Unit energy requirement related to surface abstraction;* *E_{lp} - Economic land productivity*

$I_{en(g)}$ [kwh/€]: ENERGY FOOTPRINT FOR IRRIGATION INDEX RELATE TO GROUNDWATER ABSTRACTION	$I_{en(g)} = E_{a(g)}/E_{lp}$	*Energy requirement from-source-to-field in order to get a unit revenue for the i-th crop. Calculated for each crop*	*$E_{a(g)}$ - Unit energy requirement related to groundwater abstraction;* *E_{lp} - Economic land productivity*
US_w [m³/ha]: UNIT SURFACE WITHDRAWALS	$US_w = GUI/(e_c \times e_{farm})$	*Unit amount of water abstracted from surface source, assuming the irrigation requirement completely satisfy by surface withdrawals*	*GUI_i - Total unit gross irrigation;* *e_c –conveyance efficiency;* *e_{farm} – farm efficiency;*
UG_w [m³/ha]: UNIT GROUNDWATER WITHDRAWAL	$UG_w[m^3/ha] = GUI/e_{farm}$	*Unit amount of water abstracted from groundwater source, assuming the irrigation requirement completely satisfy by surface withdrawals*	*GUI_i - Total unit gross irrigation;* *e_{farm} – farm efficiency;*
$\eta_{(s)}$: PUMP EFFICIENCY OF THE SURFACE SUPPLY SYSTEM	$\eta_{(s)} = \frac{P_{w(s)}}{P_{a(s)}}$	*Pump efficiency of the surface supply*	*$P_{w(s)}$ – Hydraulic power of surface water pumping system;* *$P_{a(s)}$ – Absorbed power of surface water pumping system;*

$\eta_{(g)}$: PUMP EFFICIENCY OF THE GROUNDWATER SUPPLY SYSTEM	$\eta_{(g)} = \frac{P_{w(g)}}{P_{a(g)}}$	*Pump efficiency of the surface supply system*	*$P_{w(g)}$ – Hydraulic power of groundwater pumping system;* *$P_{a(g)}$ – Absorbed power of groundwater pumping system;*
IRRIGATION WATER – COST FOOTPRINT INDEX			
$C_{w(s)}$ [€/ha]: IRRIGATION WATER COST RELATED TO SURFACE WATER ABSTRACTION	$C_{w(s)} = t_w \times GUI$	*Irrigation water cost related to surface water abstraction.*	*t_w – Water tariff as fixed by management authority;* *GUI_i - Total unit gross irrigation;*
$C_{w(g)}$ [€/ha]: IRRIGATION WATER COST RELATED TO GROUNDWATER ABSTRACTION	$C_{w(g)} = t_e \times E_{w(g)} \times GUI$	*Irrigation water cost related to groundwater abstraction calculated referring to the pumping cost*	*t_e – Energy tariff;* *$E_{w(g)}$ - Unit energy consumption related to groundwater abstraction;* *GUI_i - Total unit gross irrigation;*
$I_{e(s)}$ [-]: IRRIGATION WATER COST FOOTPRINT INDEX RELATED TO SURFACE ABSTRACTION	$I_{e(s)} = C_{w(s)}/E_{lp}$	*Water cost needed to withdraw water from a surface source to the field in order to get a unit revenue for the i-th crop expressed as economic land productivity*	*$C_{w(s)}$ - Irrigation water cost related to surface water abstraction;* *E_{lp} - Economic land productivity*

$I_{E(g)}$ [-]: IRRIGATION WATER COST FOOTPRINT INDEX RELATED TO GROUNDWATER ABSTRACTION	$I_{e(g)} = C_{w(g)}/E_{lp}$	*Water cost needed to withdraw water from a groundwater source to the field in order to get a unit revenue for the i-th crop expressed as economic land productivity*	*$C_{w(g)}$ - Irrigation water cost related to groundwater abstraction;* *E_{lp} - Economic land productivity*
t_w [€/m^3]: WATER TARIFF	-	*Water tariff as fixed by management authority. (0.31 €/m^3)*	*Data collected from ARIF*
t_e [€/kwh]: ENERGY TARIFF	-	*Energy tariff (0.15 €/kWh)*	*Data collected from national energy agency*

Appendix E: Participatory Workshop: Methodology Validation

Following the first workshop “Design of Policy Alternatives” organized by LAMSADE-CNRS (Laboratory for Analysis and Modelling Systems for Aid to Decision - National Research Council) as mentioned in chapter 5, in Consorzio di bonifica della Capitanata by of the University Paris-Dauphine (France) in collaboration with IRSA-CNR (Water Research Institute – National Research Council) of Bari (Italy), during the last 13rd October 2017 a second participatory workshop was organized by the same research institutes. The workshop represent the core of the proposed methodology, since the overall purpose was to fuel discussion and collective learning by local stakeholders. Particularly this workshop aimed at assessing the possible effects of innovative policies for the management and protection of water resources for irrigation use in collaboration with local community represented by farmers, regional authority and Consorzio di bonifica della Capitanata. Using the different policy alternatives generated and discussed during the previous workshop (see chapter 5), this meeting was targeted to analyse the impacts of these policies expected by the various actors on the system sustainability. To this end, the scenarios presented in chapter 5 were proposed and the obtained results were discussed with stakeholders. Moreover, it allowed to validate the conceptual model developed in this research work (Figure 15), and the capability of indicators to capture the complex dynamics of the system investigated. Indeed. Going into further detail of the workshop organization, after a briefly explanation of the methodology implemented, stakeholders were divided in two distinct mixed groups (comprising 6 people per group) an then invited to participate at two different activities related respectively to i) validation of CLD’s of the investigated system and ii)identification of expected impacts due to policy implementation. During the former activity, a simplified map was proposed to each group (see Figure E1) at which was required to validate the highlighted links (see Figure E2, E3, E4 and E5). Whereas, during the second activity it was asked to discuss about the possible implication on system of each alternative policy generated in the first workshop. Furthermore, a last query was asked to answer related to their individual perception of the sustainability.

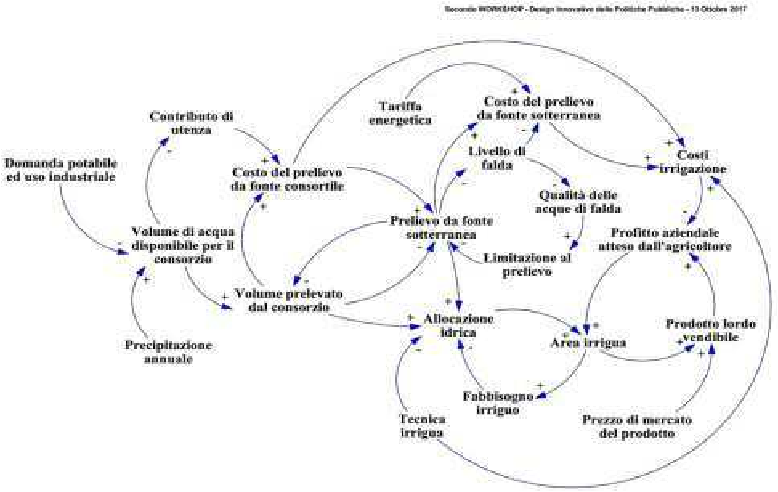

Figure E1: Simplified map of the Consorzio per la Bonifica della Capitanata system. The variables in the map were translated in Italian to facilitate the discussion

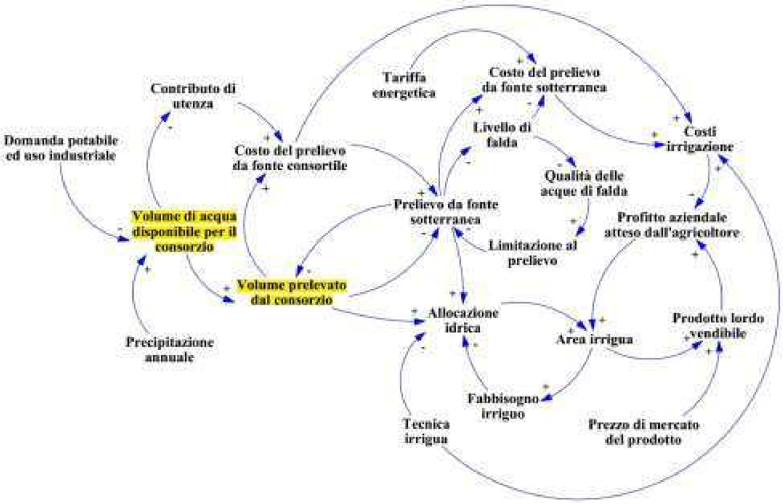

Figure E2: Simplified map with the highlighted link among water available for water management authority and water volume withdrawals from water management authority by farmers.

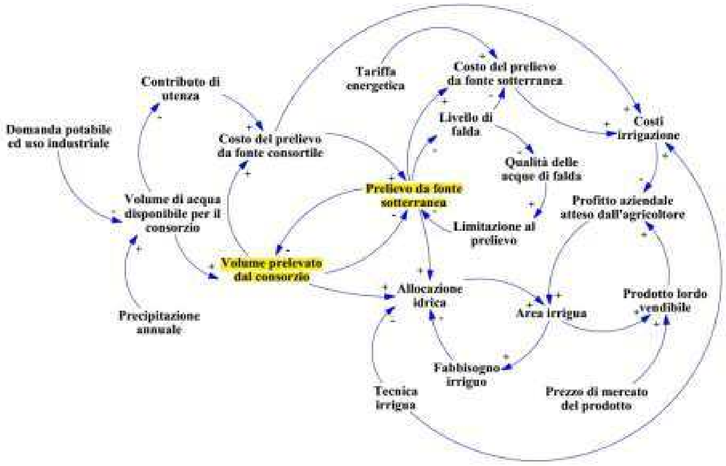

Figure E3: Simplified map with the highlighted link among water volume withdrawals from water management authority and groundwater.

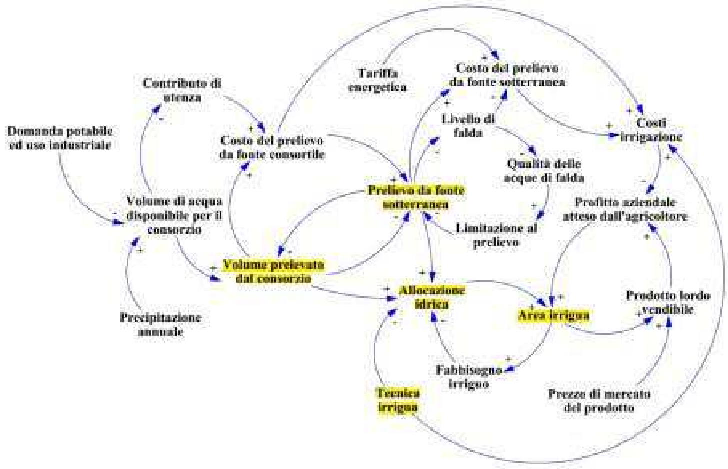

Figure E4: Simplified map with the highlighted link among water volume withdrawals from water management authority and groundwater, irrigation budget, irrigation techniques and irrigated area.

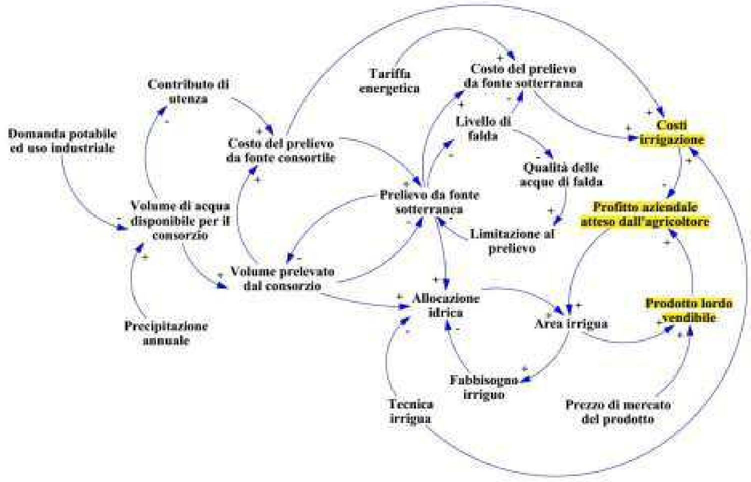

Figure E5: Simplified map with the highlighted link among expected farm profit, economic land productivity and irrigation cost.

CURRICULUM VITAE ET STUDIORUM

Informazioni personali

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Istruzione e titoli di studio

- Abilitazione all'esercizio della professione da ingegnere conseguito presso il Politecnico di Bari in data 21/01/2015 con votazione complessiva 394/400.
- Laurea magistrale in ingegneria Civile (LM-23) conseguita presso il Politecnico di Bari in data 17/04/2014 con votazione 110/110 e Lode, discutendo una tesi in Gestione dei Bacini Idrografici dal titolo "Modellazione di un sistema lacustre in zona costiera: Il caso del lago Alimini Piccolo". Di cui, il Prof. Umberto Fratino del dipartimento DICATECh del Politecnico di Bari, gli Ing.ri Ivan Portoghese, Michele Vurro e Alessandro Pagano dell'Istituto di Ricerca sulle Acque IRSA – CNR di Bari sono stati relatori.

  Le attività di tesi sono state svolte durante un tirocinio formativo della durata complessiva di 7 mesi svolto presso l'Istituto di Ricerca sulle Acque IRSA –

CNR di Bari e hanno riguardato la definizione di un modello matematico di bilancio idrologico del lago Alimini Piccolo. Attività rientrante nell'ambito di un accordo quadro tra l'IRSA e l'Acquedotto Pugliese.

- Laurea triennale in ingegneria Civile conseguita presso il Politecnico di Bari sede di Foggia in data 20/04/2010 con votazione 107/110, discutendo una tesi in Geologia Applicata dal titolo "Aspetti geologici e geotecnici relativi alla progettazione di opere di stabilizzazione di versanti in frana", con relatore il Prof. Luigi Monterisi del Politecnico di Bari.

Pubblicazioni

La sottoscritta è autrice delle seguenti pubblicazioni su rivista scientifica e a convegno:

- Portoghese, I., de Vito, R., Fratino, U., Pagano, A., Vurro, M., Caputo, M.C., De Carlo, L., and Masciale, R. "Un modello afflussi-deflussi per lo studio del bilancio idrogeologico del Lago Alimini Piccolo nella penisola Salentina", IDRA 2014, Bari;
- de Vito R., Portoghese I., Pagano A., Fratino U., Vurro M.(2015) "Water and energy efficiency in a high environmental value agricultural area" in Abstract Proceedings of the Intenational Conference IrriMed2015 – CIHEAM, Valenzano (Bari-Italy) 2015, ISBN 2-85352-549-X
- de Vito R., Portoghese I., Pagano A., Fratino U. (2015) "Integrating WFA and hydrological modelling for assessing sustainability of agriculture in a complex environmental system". Agriculture & Forestry, Vol. 61, Issue 4: 293-300, 2015, DOI: 10.17707/AgricultForest.61.4.35.
- de Vito R. "System dynamic modelling to evaluate Water-Energy-Food Nexus at local scale" oral presentation available online at https://www.wef.uni-osnabrueck.de/b1-capturing-complex-interdependencies-through-modelling/;
- de Vito R., Portoghese I., Pagano A., Vurro M., Fratino U. (2016) "Water-Energy-Food nexus: Il Water Footprint come metodo di analisi di sostenibilità in una zona ad elevata valenza ambientale" in atti del XXXV Convegno Nazionale di Idraulica e Costruzioni Idrauliche, IDRA16, pag.367;
- de Vito, R., Portoghese, I., Pagano, A., Giordano, R., Vurro, M., Fratino, U., 2017. Sustainability Assessment of agricultural production through Causal Loop Diagrams, in: Panta Rhei . Book of Abstracts of the 10th World Congress of EWRA on Water Resources and Environments. Grigoris Pubblications, 5-9 July 2017, Athens, Greece.

- de Vito R, Portoghese I, Pagano A, et al (2017) An index-based approach for the sustainability assessment of irrigation practice based on the water-energy-food nexus framework. Adv Water Resour 1–14. doi: 10.1016/j.advwatres.2017.10.027
- de Vito R, Portoghese I, Pagano A, et al (2017) Sustainability Assessment of agricultural production through Causal Loop Diagrams. European Water 381–386.

Attività didattica

La sottoscritta è stata correlatrice della seguente tesi di laurea:

- PENZA Grazia (A.A. 2015 – 2016) 'Produttività e sostenibilità della pratica irrigua in Capitanata: modellazione attraverso il water footprint assesment' tesi laurea magistrale in ing. Per l'Ambiente e il Territorio, Politecnico di Bari, dipartimento DICATECh. rel.ri Umberto Fratino, Ivan Portoghese, Rossella de Vito
- Cortese Nicla (A.A. 2017 – 2018) "Sostenibilita' Ambientale Delle Colture Irrigue In Puglia" tesi di Laurea Magistrale in ing. Civile, Politecnico di Bari, dipartimento DICATECh rel.ri Umberto Fratino, Ivan Portoghese, Rossella de Vito

Corsi di specializzazione

Nell'ambito delle attività connesse con il dottorato di ricerca ha seguito i seguenti corsi di specializzazione:

- Integrated Water Management presso University of Twente (Enschede)
- Rischio nelle infrastrutture di trasporto presso il Politecnico di Bari
- Rischio Sismico presso il Politecnico di Bari
- Salvaguardia e conservazione dei Beni storico-architettonici presso il Politecnico di Bari
- Rischio nelle infrastrutture stradali presso il Politecnico di Bari
- Economia ambientale presso il Politecnico di Bari
- Metodi matematici e numerici per l'ingegneria presso il Politecnico di Bari
- Automazione dei sistemi elettrici per l'Energia presso il Politecnico di Bari
- Calcolo delle variazioni e controllo ottimo presso il Politecnico di Bari
- Applicazioni di MATLAB presso il Politecnico di Bari
- Acquisizione ed elaborazione di dati di laboratorio e di campo presso il Politecnico di Bari

- “Water and Food Security” presso il Politecnico di Milano
- Calcolo delle probabilità e statistica presso il Politecnico di Bari

Convegni

Nell’ambito delle attività connesse con il dottorato di ricerca ha partecipato ai seguenti convegni:

Modern technologies, strategies and tools for sustainable irrigation management and governance in Mediterranean agriculture” - (IrriMed 2015) – Valenzano 23-25 Settembre 2015;
“Sixth Intenational Scientific Agricultural Symposium – Agrosym 2015” 15-18 Ottobre Jahorina (Bosnia and Herzegovina);
“Understanding the Water-Energy-Food-Nexus” Osnabruck Germany 15-16 Giugno 2016;
“XXXV Convegno nazionale di idraulica e costruzione idrauliche - IDRA 2016” 14 – 16 Settembre Bologna 2016;
EWRA 10th WORLD CONGRESS On Water Resources And Environment "PANTA RHEI" 5-9 JULY 2017 Atene;