Politecnico di Torino

Master of Science in Civil Engineering

Assessing Agricultural Water Use in Italy by Integrating Crop Irrigation Requirements and Spatial Data Analyses of Cultivated Areas

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Preface

The world that we live in is experiencing a multitude of challenges and problems. including climate change, war, pandemics, poverty, inequity, political instability, global health issues, and more. Among these issues, water-related problems are endangering humanity, whether caused by anthropogenic factors or the effects of climate change. In this context, I endeavored to harness my interest in assessing and studying some of these problems.

I would like to express my gratitude for the invaluable guidance and teachings I have received from my supervisor, Professor Tamea, over the past months. It is important to note that throughout this journey, there were instances where I felt lost.
However, I came to realize that in research, there are always ups and downs, and the key to staying on track lies in perseverance and compassion—qualities instilled in me by my dear supervisor and fueled by my genuine interest in addressing the challenges faced by humankind in this era.

I want to express my deepest gratitude to my family, especially my mother and my late father. Their unwavering support and love have been my guiding light throughout this academic journey. Though my father is no longer with us, his legacy of perseverance and curiosity continues to inspire me. My mother's constant encouragement and sacrifices have been my strength. I owe them everything, and I dedicate this thesis to them with profound gratitude.

Reza Eghbali

Abstract

Over the past decades, climate change has impacted various facets of life, notably through increasing temperatures, altered precipitation patterns, and the escalation of extreme weather events.

These impacts have critical implications for global and local water resources. Considering that the largest portion of water use in the world is for the agricultural sector, it can be concluded that agriculture is deeply interconnected with water and climate. Against the backdrop of climate change, together with the growing human needs that lead to increasing pressure on Earth's resources, the significance of agriculture in sustaining food security increases, necessitating a comprehensive understanding of water consumption patterns within the agricultural sector.

This study sheds light on water usage in agriculture in Italy. It explores official statistics at different administrative levels and gridded data to examine where, how, and for what water is used in agriculture.
To achieve this aim, a multifaceted approach integrating various datasets has been adopted.

One of the data sources implemented in this study is ISTAT (Italian National Institute of Statistics), which provides data on the agricultural census in 2010. The data are published at different spatial scales from the regional to the commune level.
Another data source used is GMIA (Global Map of Irrigation Data), which provides gridded data on the irrigated area and the percentage of the irrigated area by different resources on a global scale. Validating the GMIA data on Italian surfaces shows very small differences in all irrigation areas concerning the national census data from ISTAT.

By using the water usage data from different resources provided by ISTAT and the data provided by GMIA, a comprehensive comparison is conducted for the area irrigated by different water resources in each administrative section.
ISTAT also provides data on the area irrigated by different irrigation systems and the area irrigated by different crops.

A hydrological model developed at the Politecnico di Torino in the past has been employed in this study to estimate crop-specific evapotranspiration rates and irrigation requirements. Through the integration of irrigation requirement data and the area irrigated by different crops, the irrigated water volume required by each crop is estimated for the main crops for which information is available. The national datasets provide the spatial coverage of different irrigation systems in Italy. Due to this, by having the gridded data of irrigation requirements, the amount of water consumed by each

irrigation system for a crop is studied. Knowledge of irrigation systems also allowed us to infer, through irrigation efficiency, the water volumes withdrawn from the source.

The study results can support policymakers and stakeholders in informed decision-making. They also provide valuable insights for environmental analysis to better understand and address environmental challenges associated with the agricultural use of water.

Contents

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Acronyms and Abbreviations

ISTAT Italian National Institute of Statistics

GMIA Global map of Irrigation Area

aei,AEI Area equipped for irrigation

aai,AAI Area Actually Irrigated

aeigw Area equipped for irrigation by ground water

aeinc Area equipped for irrigation by non-conventional sources

aeisw Area equipped for irrigation by surface water

UWNH Underground water in or near the farm

SWHB Surface water on the farm (natural and artificial basins)

SWHL Surface water off the farm (lakes, rivers, or water flows)

AIRCT Aqueduct, irrigation, and restoration consortium, or other institution with delivery in turns

AIRCD Aqueduct, irrigation, and restoration consortium, or other institution with delivery on demand

OTWS Other water sources

Prov Province

COM Commune

MAIZE Grain maize

CEREAX Cereals for grain production (excluding maize and rice)

DRPUL Dried pulses

POTAT Potatos

BEETS Sugar beet

CROPTX Textile crops

RAPETR Rape and turnip rape

SUNFLO Sunflower

VEGFRO Fresh vegetables outdoor

MAIZGRE Green maize

ARLANO Other arable land crops

VINEY Vineyard

OLIV Olive plantation

CITRFR Citrus fruit

FRUIT Fruit plantations

NURSEPCROG Nurseries and other permanent crops

PGRAPM Permanent grassland, pastures, and meadows

LSRC Land with short rotation coppices connected to the holding

TGRAOT Other temporary grass

FAO Food and Agriculture Organization of the United Nations

ET Evapotranspiration

AWC Available water capacity

SOW Sowing

WP Wilting Point

fd Field capacity

PD Precipitation Days

ID Irrigation Days

SD Stress Days

LPG Length of Growing period

ASPE Aspersion(raindrop)

FLOO Flooding

MICR Micro Irrigation

SSSI Surface Sliding and Slide Infiltration

OTSY Other systems

SDG Sustainable development goal

SSP Shared Socioeconomic Pathways

IPCC Intergovernmental Panel on Climate Change

SAFA Sustainability Assessment of Food and Agriculture systems

AgMIP Agricultural Model Inter comparison and Improvement Project

GGCM Global Gridded Crop Model

ISIMIP Inter Sectoral Impacts Model Inter- comparison Project

Introduction

The Earth is abundant in water, but not all of it is readily available for human use. Approximately 97.5% of the Earth's water resides in the oceans, rendering it too salty for human consumption or agricultural use. Only a small fraction, around 2.5%, constitutes freshwater.
However, the majority of freshwater is confined in ice caps, glaciers, and underground aquifers, leaving a relatively small percentage as surface water in lakes and rivers. This surface water is easily accessible and can be utilized for various human activities, including agriculture.

Agriculture is a major consumer of water resources, accounting for a significant portion of global water usage. The exact amount varies based on factors such as climate, crop types, and agricultural practices. In many regions, irrigation is essential to support crop growth, often representing a substantial share of water consumption. The fundamental starting point for both food and life is water. Over the past century, our understanding of water management and agriculture has significantly reduced hunger, malnutrition, and poverty. Advances in knowledge and technology empower us to harness this precious resource and manage life systems effectively.
Despite this progress, clear lessons emerge from history. Inequity persists alongside abundance and prosperity, intensifying water scarcity. It is crucial to remember that without water, there is no food, and without food, there is no security.

The problems in the water sector can drastically impact agriculture, which has the highest water consumption. In many parts of the world, water and food scarcity are expected to restrict human development. The challenge arises from the increasing demand for water in agriculture due to population growth, changes in dietary habits, and urbanization.
Consequently, sustainable water management practices are crucial to ensuring efficient and responsible water resource use. This involves adopting technologies like drip irrigation, improving water use efficiency, and promoting water conservation in agricultural practices.

Additionally, while the Earth possesses a vast amount of water, only a small percentage is freshwater, and an even smaller portion is readily accessible for human use. Agriculture's significant water consumption underscores the importance of sustainable water management practices to meet the growing demand for food while preserving water availability for other essential needs.
To obtain a realistic understanding of water consumption in the agricultural sector, it is imperative to assess the potential impacts of climatic, demographic, and socio-economic changes on water use.

A crucial prerequisite for this assessment is determining the location and extent of irrigated areas.

The world's population is expected to reach 9.1 billion by 2050, and feeding this population requires raising overall food production [11] by knowing the fact that the importance of water usage and its optimization is becoming more important in the agricultural sector and at the farm level to conduct this assessment, remote sensing emerges as a valuable tool, providing new possibilities and high-resolution datasets.
Satellite data, with its impressive resolution, empowers users to gain a comprehensive understanding of on-field activities.

In this study, two primary data sources have been utilized, the first is provided by GMIA, and the second comprises data from ISTAT.
Considering the aforementioned facts, this study aims to examine the agriculture sector in Italy. The study focuses on the entire territory of Italy, utilizing the predefined administrative boundaries set by ISTAT.

Eventually, through the spatio-temporal assessment of irrigation and crop water requirements, essential for adopting proper water-related policies, governments and stakeholders will be able to gain a better understanding of current and future solutions. This understanding is crucial for aligning their policies with reality in a sustainable manner.

Chapter 1: Introduction to Data

1.1 An Overview of Data Sources

In this study, two primary data sources have been employed. Given the study's focus on irrigation data, the extraction of spatial land data was necessary. Following an examination of available global datasets, the GMIA dataset was chosen for its relevant content.
The first dataset utilized is GMIA v5, which presents the percentage of land equipped for irrigation with a spatial resolution of 5 arc minutes.
The second dataset is sourced from ISTAT, the Italian National Institute of Statistics. This organization provides detailed statistics derived from national censuses, offering more precise data for our study.

1.2 GMIA Data Set

GMIA also known as the global map of irrigation areas contains data layers on the percentage of area equipped for irrigation that is actually used for irrigation and on the source of irrigation water (groundwater, surface water, water from non-conventional sources). The count of sub-national units included in the global inventory has risen to 36090 for areas equipped for irrigation, 10316 for areas actually irrigated, and 14483 for statistics on irrigation water sources. Reference years for these statistics vary across countries and variables but typically fall from 2000 to 2008. In version 5 of this dataset, the total global area equipped for irrigation stands at 307.6 million hectares, out of which 255.2 million hectares (83 percent) were actually irrigated. Among these, 116.2 million hectares (38 percent of the total equipped area) were facilitated for irrigation with groundwater, 191.2 million hectares (62 percent) for surface water irrigation, and 0.3 million hectares (0.1 percent) for irrigation sourced from non-conventional water sources[13].

The first version of the Digital Global Map of Irrigated Areas was published in 1999. It consisted of a raster map with a resolution of 0.5 ° by 0.5 ° containing the percentage of the area that was equipped for irrigation around 1995, the so-called irrigation density. To further develop and improve the global GIS coverage of areas equipped for irrigation and to make it available to users in the international community, cooperation was established between the Johann Wolfgang Goethe University in Frankfurt, Germany, the Rheinische Friedrich-Wilhelms-Universität Bonn, Germany, and the Land and Water Division of the Food and Agriculture Organization of the United Nations (FAO)[14].

1.2.1 Methods for Mapping of Area Equipped for Irrigation

The data layer concerning irrigated areas was created by merging regional irrigation statistics with geospatial data on the location and size of irrigation projects. This process calculated the proportion of 5 arc minute cells equipped for irrigation, known as irrigation density. Information on irrigation, obtained from national census surveys and various international organizations such as FAO and the World Bank, is continuously gathered at the sub-national level (e.g., districts, counties, provinces)[13]. When multiple years of data are available, statistics from the year closest to 2005 are utilized.

In cases where AQUASTAT database statistics are deemed more representative at the country level, the collected subnational data is adjusted to ensure the total irrigated area matches the country-level irrigation data provided by AQUASTAT.
For most countries, irrigation statistics pertain to the area equipped for irrigation. However, factors like crop rotation, water scarcity, and infrastructure damage can lead to discrepancies between the equipped area and the actual irrigated area, with the latter often being lower.

Some countries only report the actual irrigated area during census years. In such instances, the equipped irrigation area is estimated by analyzing a time series of actual irrigation areas over several years (e.g., five years) and selecting the maximum reported irrigated area at the highest available resolution. To gain a deeper comprehension of the methodology employed for mapping the irrigated area provided by GMIA and to grasp the hierarchy involved in data collection, the following scheme is presented: paying attention to the data collection methodology helps us to understand the source of the probable error and lack of accuracy in the data set. Since in some regions of the world given data are more precise therefore the data precision might vary country by country and region by region

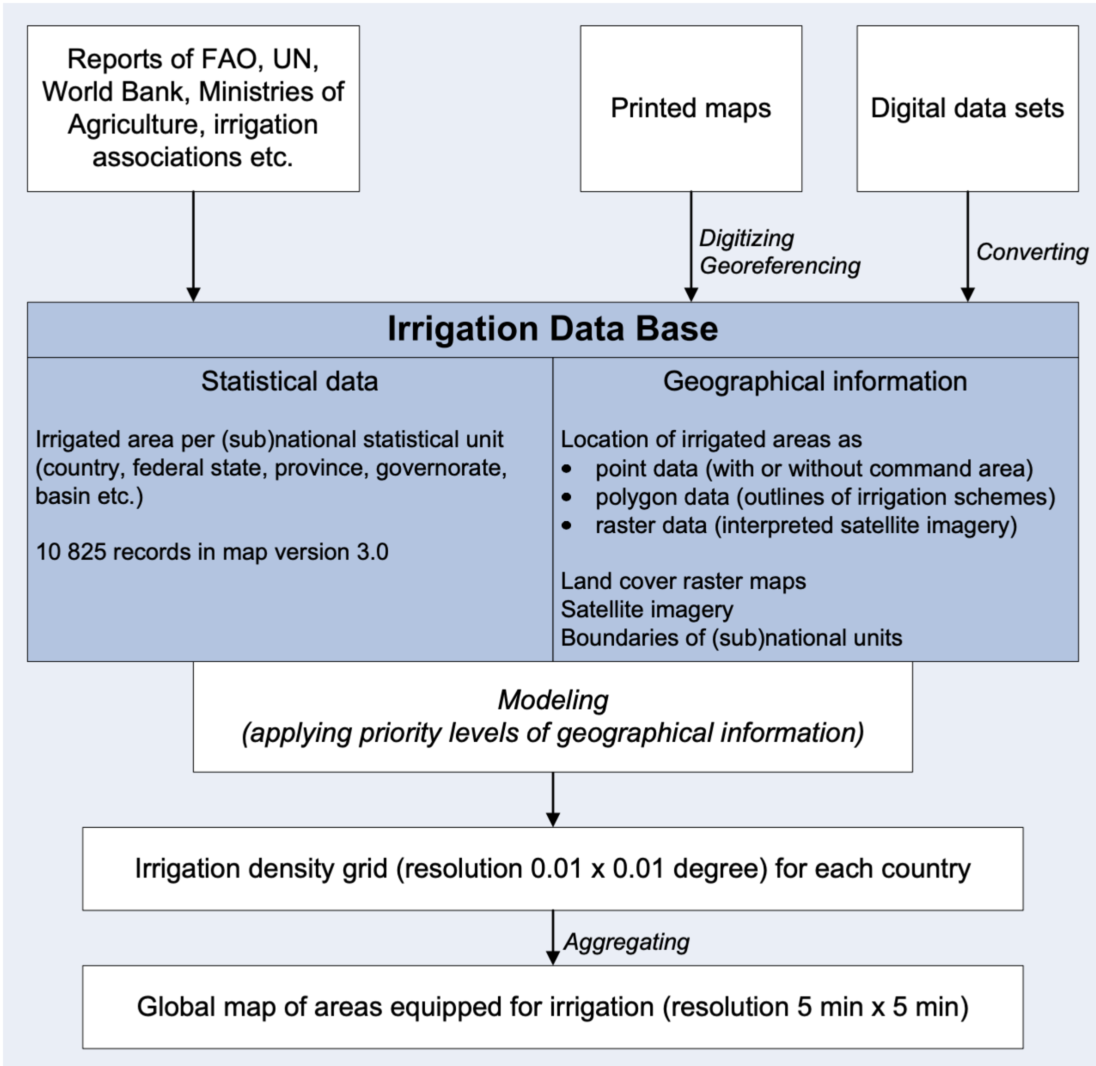

Figure 1: Scheme of mapping methodology used to develop the Global Map of Irrigation Areas[13]

1.2.2 GMIA Data Quality

The spatial quality of the GMIA dataset varies across regions and is not consistent everywhere. The maps illustrate the subnational units with available irrigation statistics (left) and the assigned quality marks for each country (right) concerning the area equipped for irrigation, the actual irrigated area, and the water source for irrigation.
In most countries, the statistical data originates from the period between 2000 and 2008.

According to the GMIA documentation, Italy demonstrates very good map quality regarding the area equipped for irrigation, good quality for the actually irrigated area, and poor quality for the water source.

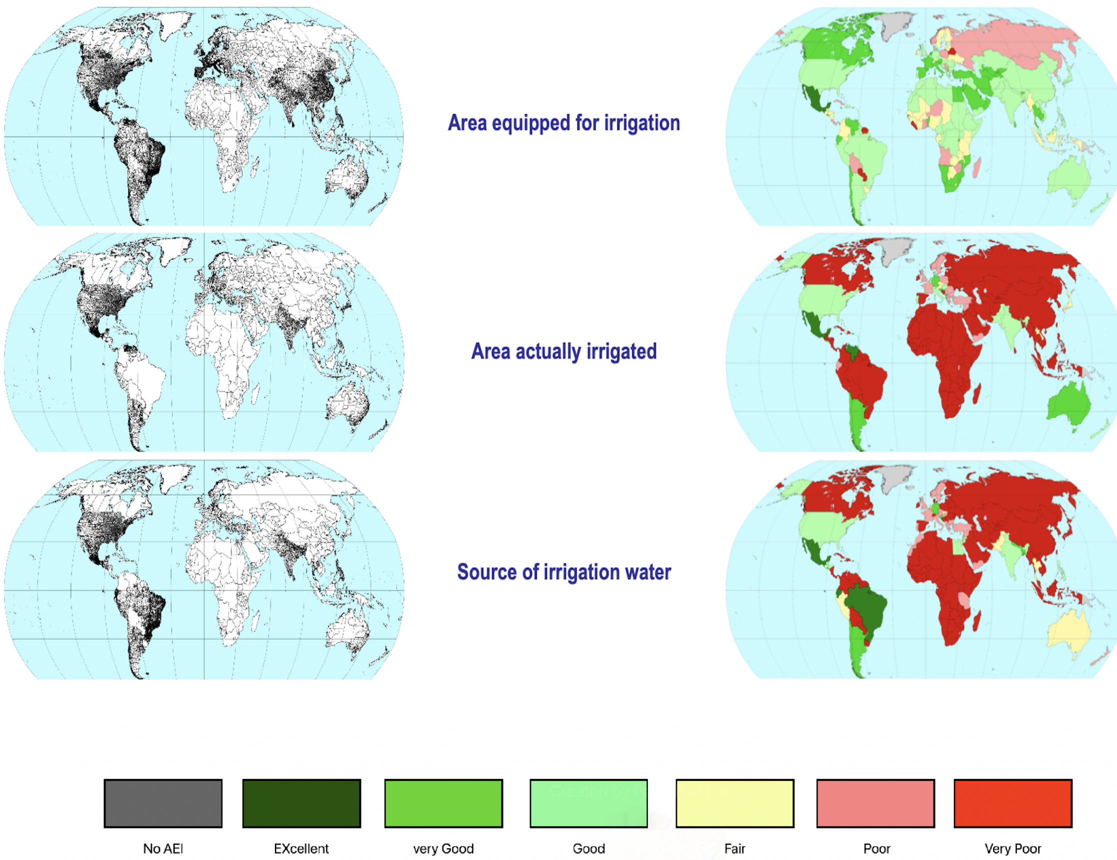

Figure 2: The digital global map of irrigation areas[13]

1.3 ISTAT Data Set

The Italian National Institute of Statistics also known as ISTAT, is a public research organization, that serves as the principal producer of official statistics dedicated to citizens and policy-makers. Operating with complete independence, ISTAT maintains continuous interaction with academic and scientific communities. The datasets generated by ISTAT are compilations of data disseminated without regular frequency.
Typically, these datasets are produced upon the conclusion of surveys, representing a

preliminary form of data publication. The datasets are accessible in spreadsheet format and are accompanied by introductory and methodological notes.

Italy conducts its agricultural census once every decade. This study utilizes data from the sixth agricultural census, which was conducted with a reference date of October 24, 2010. The census period encompasses the agricultural marketing year from November 1, 2009, to October 31, 2010, providing information on land use, agricultural practices, and animal production methods. Moreover, it includes data from the 12 months preceding October 24, 2010, concerning the professional status of agricultural holders, and information on landscape features spanning the last three years (2008-2010).

The geographical coverage of the census encompasses the entire country, and the data collection approach involves two techniques: face-to-face interviews and self-interviewing methods.

1.3.1 Data Warehouse Specification of the Agricultural Census of 2010

The data warehouse of the 6th General Census of Agriculture offers a comprehensive repository of detailed information concerning the structure of Italian agricultural and livestock holdings, meticulously disaggregated to the municipal level.

The statistics within the warehouse are organized around two primary themes including data about the holding and data associated with the municipality of the land/farms' location. Data concerning the holding are further categorized into six sub-levels, encompassing the structure of farms, crops, livestock, labor, other activities, and time series, facilitating comparisons of key variables with the data from the three preceding agricultural censuses.

On the other hand, data pertaining to the municipality of the land or farms' location are split into two sub-levels: land use by agricultural unit location and livestock by agricultural unit location. These valuable datasets are accessible to the public via the official webpage.

Chapter 2: Spatial Data Analysis

2.1 Irrigated Area by Different Irrigation Systems According to ISTAT Data

ISTAT defines five different irrigation systems, which include surface sliding and slide infiltration, aspersion (raindrop), micro irrigation, and other systems.
For each of these irrigation systems, the area of irrigated land is reported in each commune and province. By utilizing shapefiles of the Italian territory and masking the layers using the QGIS tool, a vector file of the irrigated area for each irrigation system was created. Subsequently, by converting the vectorized layer to a raster layer with the common resolution used in this study (0.08333 degrees), the result provides grid data for the different irrigation systems. The below figures show the spatial dispersion of the sum of the area irrigated by all irrigation methods in Italy.

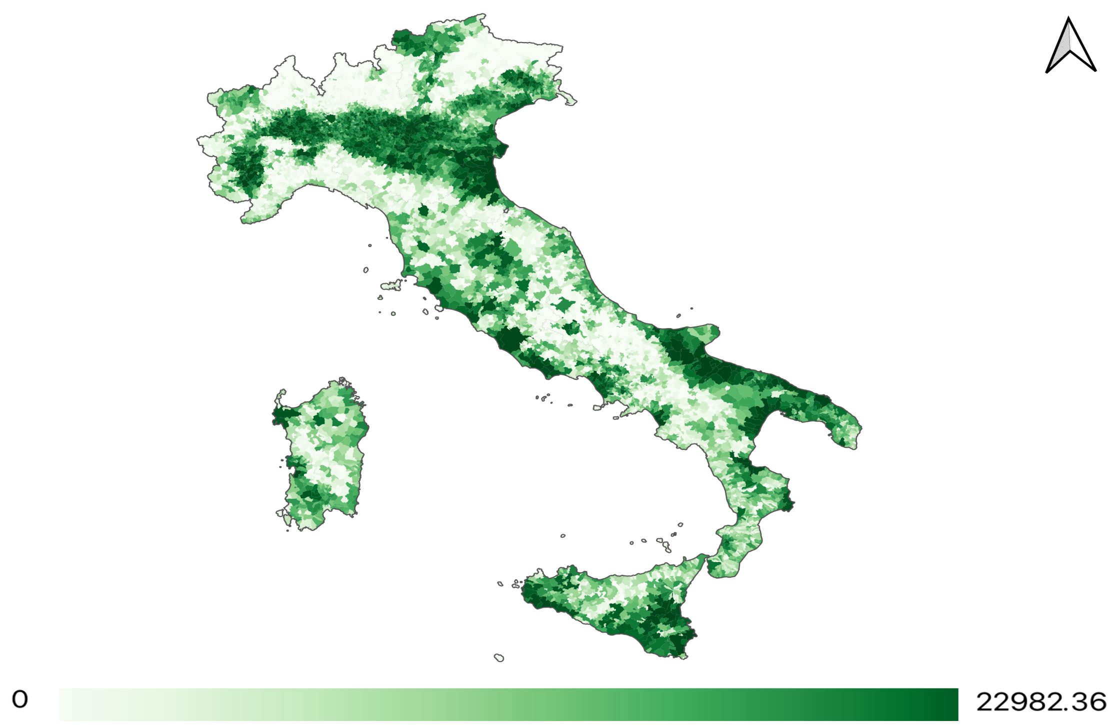

Figure 3: Sum of the irrigated areas by all Irrigation systems in Italy

The pie charts below represent the distribution of the irrigated area by different irrigation systems in Italy and Piemonte.

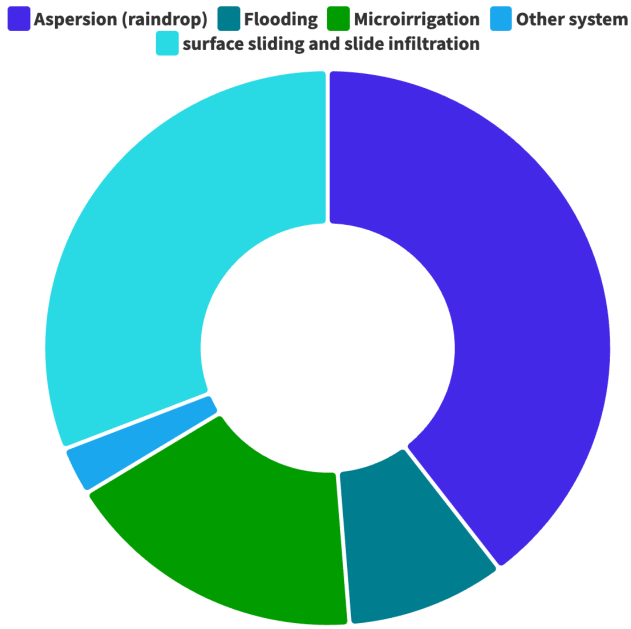

Figure 4: Area irrigated by different systems in Italy (ha)

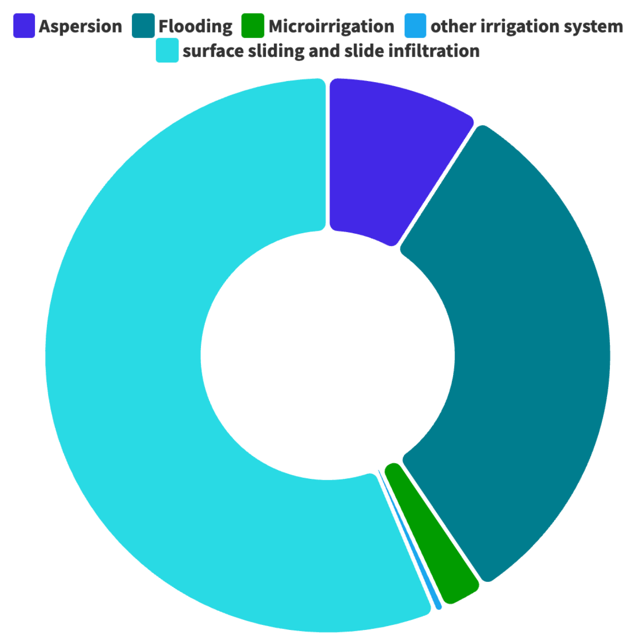

Figure 5: Area irrigated by different systems in Piemonte (ha)

Table 1: Irrigated areas in Italy and Piemonte by irrigation system

Irrigation System	Italy (ha)	Piemonte (ha)
Aspersion	958535.14	32845.9
Flooding	221024.76	116106.34
Microirrigation	422534.39	9282.45
Other irrigation system	68435.53	2094.81
Surface sliding and slide infiltration	748390.88	205929.69

Regarding the reported values by ISTAT in Italy, the largest irrigated area utilizes Aspersion irrigation, accounting for nearly 40%. Following closely is Surface Sliding and Slide Infiltration, constituting 31%, trailed by Micro Irrigation with a share of 17.5%, and other irrigation systems making up approximately 3%.

In the case of Piemonte, the predominant irrigation system is Surface Sliding and Slide Infiltration, encompassing nearly 56% of the total irrigated area. Flooding comes next, covering approximately 32% of the irrigated area, followed by Micro Irrigation at 2.5%, and other irrigation systems at less than one percent.

2.2 Irrigated Area by Different Crops According to ISTAT Data Set

ISTAT provides comprehensive data on irrigated areas devoted to various crops across different administrative levels. The table below represents the crop types, their respective acronyms, and the corresponding amount of irrigated area:

Table 2: Irrigated Area by Different Crops

Acronym	**Crop**	**Italy (ha)**	**Piemonte (ha)**
MAIZE	Grain maize	519080.76	111372.7
RICE	Rice	245824.38	121421.39
CEREAX	Cereals for grain production (excluding maize and rice)	129870.87	18716.43
DRPUL	Dried pulses	12090.53	1661.86
POTAT	Potato	21594.06	857.67
BEETS	Sugar beet	25201.74	510.92
CROPTX	Textile crops	1579.38	146.66
RAPETR	Rape and turnip rape	4354.95	565.1
SUNFLO	Sunflower	5516.36	218.02
VEGFRO	Fresh vegetables outdoor	228982	7167.53
MAIZGRE	Green maize	191148.8	18318.91
TGRAOT	Other temporary grass	185400.33	22760.86
ARLANO	Other arable land crops	79115.76	3321.15
VINEY	Vineyard	176007.05	179.99
OLIV	Olive plantation	129996.21	452.65
CITRFR	Citrus fruit	112955.71	3.58
FRUIT	Fruit plantations	194523.61	17689.36
NURSEPCROG	Nurseries and other permanent crops	12246.27	798.66
PGRAPM	Permanent grassland, pastures, and meadows	135839.57	37701.42
LSRC	land with short rotation coppices connected to the holding	7592.36	2394.33

The chart below offers a graphical representation of the data, suggesting that in Italy, the area irrigated by MAIZE surpasses that of other crops, with RICE ranking a distant second. Moreover, in the Piemonte region, RICE occupies the largest portion of the irrigated area, followed by MAIZE in second place.

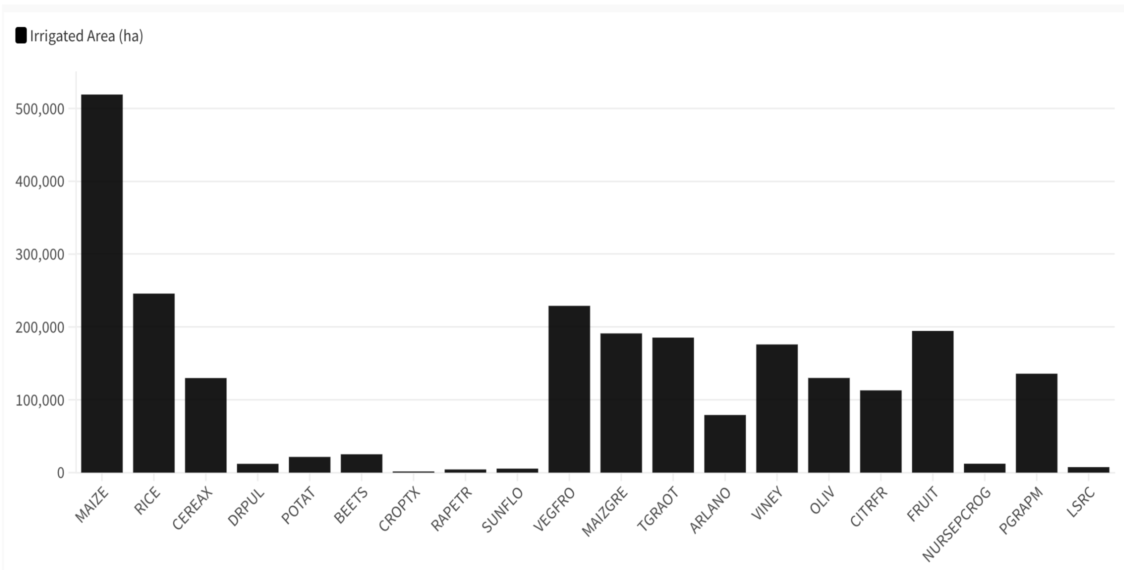

Figure 6: Irrigated area by crops in Italy (ha)

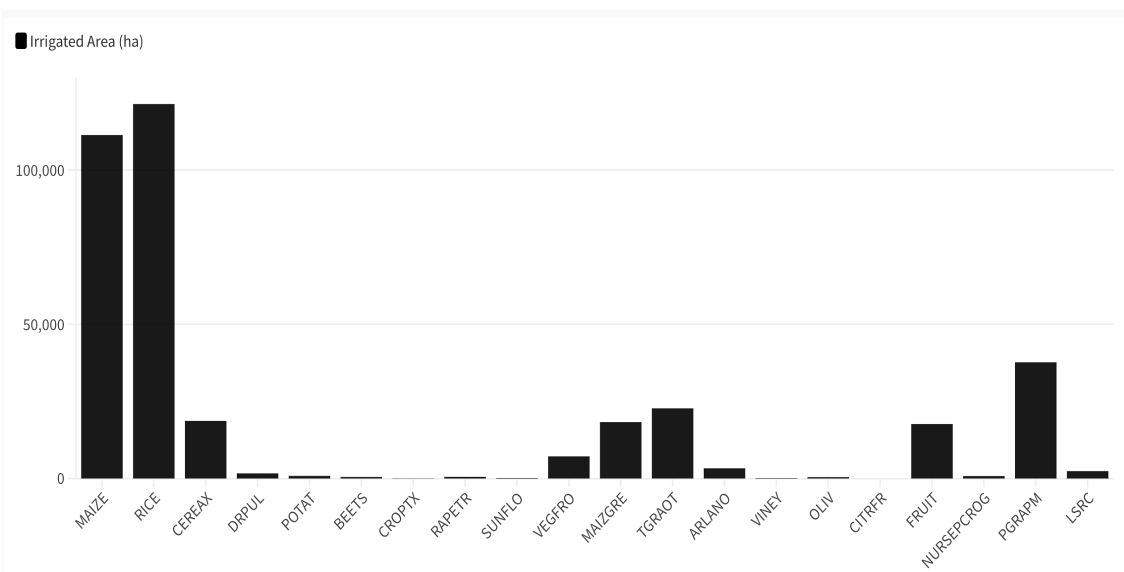

Figure 7: Irrigate area by crops in Piemonte (ha)

2.3 Comparison of Irrigated Area by Source Between ISTAT and GMIA

Through the retrieval of GMIA data from the Food and Agriculture Organization (FAO), we've acquired raster files encompassing below, which include the following key components, all the below files are grid data with a resolution of 5 arcmin.

1. ***gmia_v5_aai_pct_aei.asc*:** Represents the percentage of the equipped area that is actually irrigated.
2. ***gmia_v5_aei_ha.asc*:** Represents the area equipped for irrigation in hectares per cell.
3. ***gmia_v5_aei_pct.asc*:** Represents the percentage of the area equipped for irrigation per cell.
4. ***gmia_v5_aeigw_pct_aei.asc***: Represents the percentage of the area equipped for irrigation that is irrigated by groundwater.
5. ***gmia_v5_aeinc_pct_aei.asc***: Represents the percentage of the area equipped for irrigation that is irrigated by non-conventional sources.
6. ***gmia_v5_aeisw_pct_aei.asc*:** Represents the percentage of the area equipped for irrigation that is irrigated by surface water.

By using the raster data of the GMIA, which contains the percentage of the actual irrigated area and the percentage of the area equipped for each irrigation method in each cell, and having the area of the irrigated area in hectares, it is possible to determine the actual irrigated area in hectares in each cell for each irrigation source.
The following equation illustrates the raster calculation conducted to obtain the irrigated area for all three irrigation resources, which are groundwater, surface water, and non-conventional water resources. in the case of Italy, the non-conventional water resources are neglected since the value is very small, in the below equation, AAI_{pct} the percentage of the actually irrigated area, ${AEI_{\text{pct}}}^{\text{GW}}$ represents the percentage of the area equipped for irrigation with groundwater in each pixel, ${AEI_{\text{pct}}}^{\text{SW}}$ represents the percentage of the area equipped for irrigation with surface water in each pixel and AEI_{ha} stands for the equipped area for all irrigation sources in a hectare.

$$AAI_{\text{pct}} \cdot AEI_{\text{pct}}^{\text{GW}} \cdot AEI_{\text{ha}} = AAI_{\text{ha}}^{\text{GW}} \tag{1}$$

$$AAI_{\text{pct}} \cdot AEI_{\text{pct}}^{\text{SW}} \cdot AEI_{\text{ha}} = AAI_{\text{ha}}^{\text{SW}} \tag{2}$$

$$AEI_{\text{ha}} \cdot AAI_{\text{pct}} = AAI_{\text{ha}} \tag{3}$$

For ISTAT data, the area irrigated with each irrigation resource is available at the finest level, which is the commune level.
A vector layer of the irrigated area for each irrigation resource is created, and the conversion to raster is implemented using the QGIS tool. By estimating the area irrigated by different irrigation resources according to ISTAT with the same resolution as the GMIA data, it is possible to compare these two datasets.

Upon comparing all the irrigated areas in the study area, it is evident that the amount of irrigated area is almost equal in both data sources, and the error is almost negligible. However, comparing the data of the irrigated area by different resources is a bit challenging since the categorization of irrigation resources differs between the two datasets, and there is no further available information to align the irrigation resources. Therefore, simplified assumptions are made based on the definitions of the resources.ISTAT represents the water resources as follows:

- UWNH: underground water in or near the farm
- SWHB: surface water on the farm (natural and artificial basins)
- SWHL: surface water off the farm (lakes, rivers, or water flows)
- AIRCT: aqueduct, irrigation, and restoration consortium, or other institution with delivery in turns
- AIRCD: aqueduct, irrigation, and restoration consortium, or other institution with delivery on demand
- OTWS: other water sources

In this study, UWNH is assumed to be equivalent to the groundwater of the GMIA dataset, and SWHB, SWHL, AIRCT, and AIRCD are assumed to be equivalent to the surface water of the GMIA dataset.
Concerning the mentioned assumptions, the comparison between the amount of irrigated area conducted and the sum of the irrigated area by all types of water resources yields an error of 0.12%. The error in the amount of area irrigated by surface water is 3.3%, while the error in irrigated areas with groundwater is 19.9%. The minor discrepancy in the sum of the irrigated areas suggests a perfect match between the two datasets, thus confirming the validity of the comparison.
However, the significant deviation in the area irrigated by groundwater results from the initial assumption. It should be noted that not all of the AIRCT and AIRCD necessarily pertain to surface water. Another potential source of error arises from the map quality of the irrigated sources in the GMIA dataset, as previously discussed.

A comprehensive analysis was also conducted to visualize the differences in and dispersion of the differences between the two data sources in the study area. These differences are illustrated in grid data with a resolution of 0.08333 degrees, as well as at the province and commune levels.
The differences between the two datasets for each resource at each administrative level are shown below.

Table 3: Irrigated Areas in Italy (ha)

	Groundwater (ha)		**Surface Water (ha)**		**Total (ha)**	
	COM	PROV	COM	PROV	COM	PROV
GMIA	816445.25	775083.67	1754942.30	1658161.31	2571387.60	2433244.99
ISTAT	616329.59	620838.93	1713028.66	1713028.66	2418920.70	2430342.53
Difference	200115.66	154244.74	41913.64	−54867.35	152466.90	2902.46
ERROR %	24.51	19.90	2.39	3.31	5.93	0.12

In the map below, the spatial visualization of the differences between the two datasets is shown. The maximum difference in commune level belongs to ***Cerignola***, amounting to 10498.64 hectares this amount is 0.43% of the total irrigated Area. At the province level, the maximum difference pertains to ***Barletta-Andria-Trani***, totaling 15662.34 hectares this amount is equal to 0.64% of the whole irrigated area. Therefore as it is depicted the difference between the two data sets in each administrative level in the worst case is less than 1% of the all irrigated area.
This difference is negligible, by referring to the spatial visualization, it can be concluded that the data is trustworthy in the areas with a lower difference between the two data sets.

It's worth mentioning that, with respect to the GMIA's quality assessment of irrigation maps, the quality of mapping for the area equipped, actually irrigated area, and source of water are categorized as very good, good, and poor respectively. The results of the analysis confirm this fact, as the error in the total area of irrigation is low, but it increases when considering the area irrigated by different resources

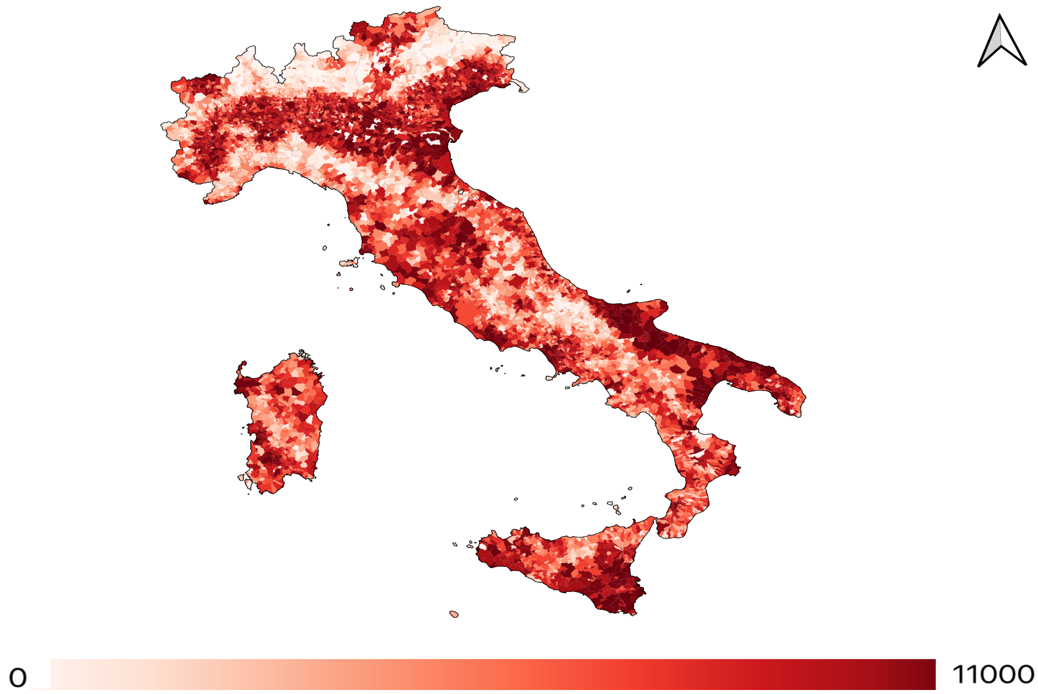

Figure 8: Differences of Irrigated area at commune level

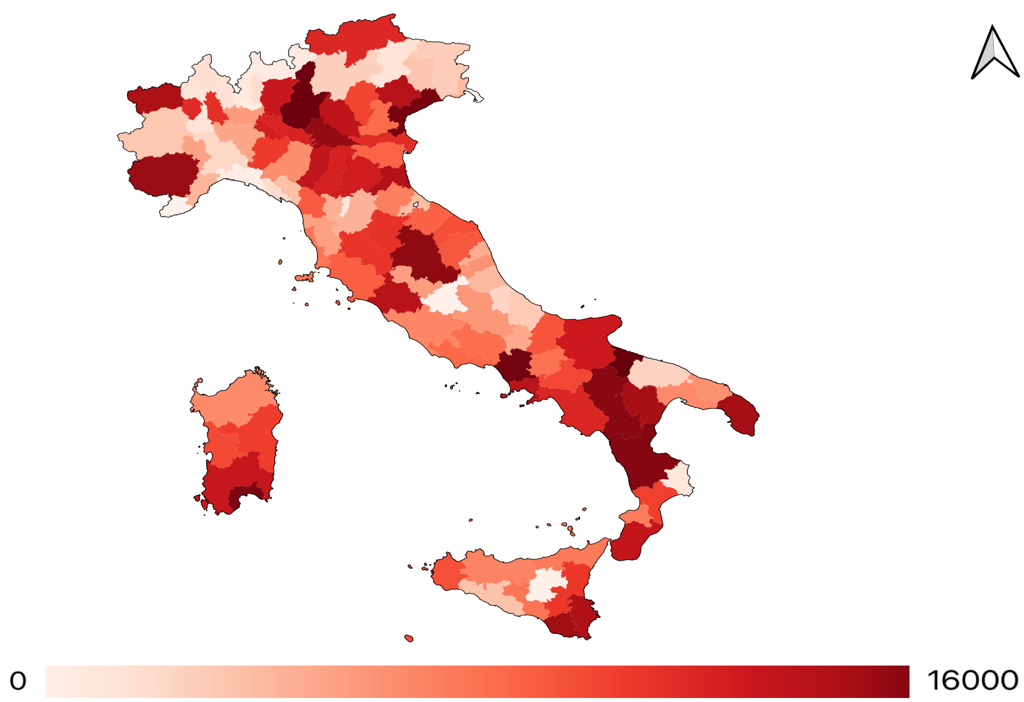

Figure 9: Differences of the irrigated area at Province level

Chapter 3: Water Requirements

3.1 Evapotranspiration

The concept of evapotranspiration is crucial in assessing water consumption by crops. The present study utilizes this model to determine the amount of water consumed.

Evapotranspiration, introduced by the Food and Agriculture Organization of the United Nations (FAO), is defined as "the combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration" (FAO). Since both evaporation and transpiration occur simultaneously, distinguishing between them is challenging.
Hence, the notion of evapotranspiration *ET* becomes necessary. The *ET* rate expresses the amount of water lost from a cropped surface in units of water depth, typically measured in millimeters (mm) per unit time[3].

According to FAO guidelines, there are three types of evapotranspiration[3]:

1. **Reference evapotranspiration (ET_0)**: This is the evapotranspiration rate from a reference surface, such as a hypothetical grass reference crop with specific characteristics (height of 0.12 m and albedo equal to 0.23). ET_0 depends solely on climate parameters.

2. **Crop evapotranspiration (ET_c)**: This is the evapotranspiration rate from a crop under standard (optimal) conditions, including disease-free, well-fertilized conditions, and optimal soil water conditions, achieving full production under the given climatic conditions. It is calculated by considering a crop coefficient (k_c) to account for specific crop characteristics.

$$ET_c = k_c \cdot ET_0 \tag{4}$$

3. **Actual evapotranspiration (ET_a)**: This is the evapotranspiration from crops grown under management and environmental conditions differing from standard conditions. It depends not only on weather and crop characteristics but also on specific field conditions and agricultural practices. The water stress coefficient (k_s) is introduced to represent the effects of water insufficiency on plant development.

$$ET_a = k_s \cdot ET_c \tag{5}$$

The crop coefficient (k_c) for a given crop changes from sowing until harvest due to variations in crop characteristics throughout its growing season (initial stage, growth, mid-season, senescence). The water stress coefficient (k_s) varies from 0 to 1 and depends on the water content of the soil. A k_s value of 1 indicates no water stress (sufficient available water for the plant), while a k_s value of 0 corresponds to the wilting point (plants cannot grow properly).

3.2 State of the Art of Crop Evapotranspiration Model

There has been significant attention in recent years about crop irrigation requisites, and in the past years, numerous studies have been conducted for the estimation of irrigation requirements for food production using crop-gridded models. The studies are done on different spatial scales (regional, continental, or national scales).

AgMIp (Agricultural Model Intercomparison and Improvement Project) is one of the comprehensive works that is intercomparison between multiple gridded crop models (GGCMs). Another important project is ISIMIP (Inter Sectoral Impacts Model Intercomparison Project)[10].
It assessed seven GGMs associated with five global climate models. There are also other various projects on a global scale, but the importance of accuracy has become more necessary for adaptation strategies recently; therefore, the importance of the spatial resolution of water requirements has increased.
Over the years, the resolution of the different models has increased, and thanks to the corp evapotranspiration model developed by Politecnico di Torino, now the evapotranspiration and irrigation requirement data is available on a daily basis.

3.3 Crop Evapotranspiration Model

climatic spatiotemporal variability emphasizes the importance of considering the variability of climate across space and time when studying irrigation requirements and their changes over time.
Climate factors such as temperature, precipitation, humidity, and wind patterns can vary significantly from place to place and can change over different periods, from hours to centuries. A Proper study involves thorough analysis and consideration of how climate variability impacts water needs for irrigation.
Climate change, driven largely by human activities such as greenhouse gas emissions, has profound effects on agriculture. It alters temperature and precipitation patterns, disrupts ecosystems, and affects the availability of water resources.
These changes impact both rain-fed agriculture (dependent solely on rainfall) and irri-

gated agriculture (where water is supplied artificially). Agriculture can rely on rainfall alone (rain-fed) or utilize irrigation systems to supply water to crops. Both types of agriculture are affected by climate change, albeit in different ways.
Changes in precipitation patterns can directly affect rain-fed agriculture, while alterations in water availability and evapotranspiration rates can impact irrigated agriculture. Therefore, considering the spatiotemporal variability of climate is essential for accurately assessing irrigation requirements and understanding how they evolve over time.

To address this concern climate-driven trends in agricultural water requirements[9] have provided the irrigation requirements and Evapotranspiration data on a grid level. To achieve this, existing soil water balance and crop growth model[8] is utilized for estimating the daily actual evapotranspiration of 26 main crops acquired over five decades.
This model offers the opportunity to consider the temporal climatic fluctuations.
The model accounts for the fixed value of rain-fed and irrigated cropland area over time, thus the only variable factor is hydro-climatic drivers. so, the conducted analyses are independent of the harvested area.

Therefore the analysis of the crop evapotranspiration in this study depends solely on meteorological changes over time. For estimating the ET_a the assumption is that no water stress occurred in crops and minimum water provided following Food and Agriculture Organization (FAO) guidelines[2].
The model, originating from[15] and presented in[8], is here applied globally from 1970 to 2019.

The assessment follows the growing monthly season from MICRA 2000[7] with a spatial resolution of 0.083333 degrees.
Crop categories include perennial crops such as fruits (permanent crops) and temporary crops like maize and wheat, which are sown and harvested within the same year.
The model operates at a daily time step using precipitation (P) and reference evapotranspiration ET_0, defined as the evapotranspiration from an ideally well-watered grass surface [2].
Daily precipitation is calculated by summing hourly rainfall from 1:00 a.m. to 0:00 of each day, while daily reference evapotranspiration ET_0(in mm d-1) is calculated using the Hargreaves–Samani method[6].

$$E_{T0,i} = k_{HS} \cdot R_{a,i} \cdot (T_{\text{mean},i} + 17.8) \cdot \sqrt{T_{\text{max},i} - T_{\text{min},i}} \tag{6}$$

Here k_{hs} is an empirical coefficient (fixed to 0.0023) in the original formula[6].
$T_{max,i}$, $T_{min,i}$ and $T_{mean,i}$ are respectively the maximum, minimum, and mean temperatures for the *i*th day (in °C) and $R_{a,i}$ is the equivalent evaporation (in mm), calculated

as the ratio between the top-of-atmosphere radiation and the latent heat of vaporization of water $(1/\lambda = 0.408)$. Temperature and radiation are daily-averaged ERA5 data. The value of 17.8 in the equation imposes a null ET_0 when
$T_{\text{mean}} = -17.8°\text{C} \approx 0°\text{F}$,
Although Hargreaves–Samani is one of the methods suggested by FAO to calculate ET_0[2].
The empirical coefficient K_{hs} in equation(6) has been calibrated to each pixel to reproduce the annual value of $ET_{0,i}$ available from a reference application of the Penman–Monteith method.

3.3.1 Soil Properties

The amount of water a crop can draw for its needs is related to soil properties known as water-holding capacity[2].
The field capacity (θ_{fc}) [m^3water/m^3soil] represents the upper limit of soil moisture after drainage, while the wilting point (θ_w) [m^3water/m^3soil] represents the dry condition at which the crop stops evapotranspiration.
The difference between the two limits is called available water capacity (AWC) and represents the maximum quantity of water that crops can withdraw from the soil[9].

3.3.2 Evapotranspiration and Irrigation

According to the [2], crop development has four phases, that are associated with specific evapotranspiration non-dimensional coefficients K_c governing the well-watered evapotranspiration rate. The crop-specific details of the growing phases are explained by Chapagain and Hoekstra [4] for ten climatic regions of the world, according to the agro-ecological classification proposed by FAO [1].

The daily crop evapotranspiration ET_c (mm d^{-1}) is defined for well-watered fields as the product between reference evapotranspiration ET_0 and the crop-specific coefficient k_c. The daily actual evapotranspiration ET_a (mm d^{-1}) also takes into account the reduction due to water stress when soil moisture drops below θ^*.[9].
θ^* is defined as the threshold of the water stress for the specific crop which is based on the crop's sensitivity to soil water.
According to the methodology proposed by FAO[2], ET_c is calculated according to

$$ET_{a,i} = ET_{0,i} \cdot k_{c,i} \cdot k_{s,i} \tag{7}$$

where ET_0 is the reference evapotranspiration of the i day (mm d^{-1}), k_c is the

non-dimensional crop coefficient that depends on the development phase, and k_s (-) is a water-stress coefficient depending on the daily soil moisture condition and the crop-specific sensitivity to soil moisture decreases.[8]
When $k_s = 1$, no water stress occurs, while $k_s = 0$ means that the crop has reached the wilting point.

The irrigation requirement (I) is consistent with the definition given in [8].
it represents the lowest amount of water required by the crop to prevent water stress and maintain evapotranspiration at ET_c levels. Crops cultivated in regions equipped with irrigation (AEI) should receive a daily supply of water to prevent water stress, ensuring they reach the minimum soil moisture level where water stress is averted.

The initial soil moisture is an important factor for temporary crops and must be determined in the sowing season, as it cannot be obtained from the soil water balance directly.
Assuming the initial soil moisture is considered to be 50% of AWCS [12], the impact of initial soil moisture on ET_a and (I) is considered for temporary crops[9].
Two limit values of initial soil moisture are considered: $\theta_{\text{sow}} = \theta_{\text{fc}}$ and $\theta_{\text{sow}} = \theta_{\text{wp}}$ at the beginning of the temporary growing season. The global area-weighted average of ET_a and *I* is estimated for both irrigated and rainfed areas.

The findings indicate that if the growing seasons of temporary crops begin when the soil moisture is minimal (wilting point), the global amount of water lost through evaporation and transpiration decreases by 12% compared to when the seasons start with maximum soil moisture (field capacity).
Additionally, the need for irrigation (excluding rice) increases by approximately 3% when all temporary crop seasons commence at the wilting point.
In essence, starting crop growth in drier soil conditions reduces water loss but increases the demand for irrigation to support crop growth.

For assessing the daily water requirements, long-term simulations can be conducted on a daily scale using meteorological data spanning over 70 years.
For each crop, precipitation events (PD, i.e., precipitation days) are defined as rainfall exceeding 2 mm per day. Based on this definition, the number of days each crop needs irrigation can be calculated from ERA5 dataset.
PD (precipitation days) are then compared with the days the crop requires irrigation ID (irrigation days) based on the mentioned assumption.

In rain-fed areas where there is irrigation, to avoid water stress (days with $k_s < 1$), the number of water-stressed days for each crop was computed and indicated with SD [9].
W_{SD} represents the number of water stress days throughout the year *y* on the *j* pixel,

calculated as the ratio between the sum of SD on rainfed areas and the sum of the respective length of the growing period (LGP days) in each pixel. The SD factor can be utilized to normalize the number of water stress days in each pixel.

$$w_{\mathrm{SD}y,j} = \frac{\sum_{c=1}^{26} \mathrm{SD}_{y,c,j}}{\sum_{c=1}^{26} \mathrm{LGP}_{c,j}} \tag{8}$$

3.4 Model Output

The results of the model computation are disseminated as grid data in NetCDF files with a resolution of 0.083333 degrees. These results encompass irrigation requirements, evapotranspiration, and the number of days required for irrigation. In this study, the irrigation requirements and crop evapotranspiration are instrumental in achieving the desired outcomes.

3.4.1 Actual Evapotranspiration (mm)

Actual evapotranspiration takes into account the effect of water stress on the crop. It is calculated by multiplying the crop evapotranspiration by the water stress coefficient. This forms the core data of the model in rain-fed situations.

3.4.2 Crop evapotranspiration(mm)

crop evapotranspiration calculated according to the growing phase assuming always well-watered conditions (no water stress).

3.4.3 Green Evapotranspiration (mm)

Green evapotranspiration (ET_{green}) represents the portion of actual evapotranspiration supplied by precipitation,and soil moisture. On the other hand, blue evapotranspiration (ET_{blue}) refers to the water used by crops supplied by surface water and groundwater resources.

The equation below representing actual evapotranspiration (ET_a) is as follows:

$$ET_a = ET_{\text{green}} + ET_{\text{blue}} \tag{9}$$

3.4.4 Irrigation Requirements (mm)

Irrigation requirements represent the minimum water depth necessary for a crop during its growing season to prevent water stress when precipitation is insufficient. Theoretically, the irrigation requirement is the amount of water needed for the crop to achieve maximum production efficiency. However, this value may not equate to the actual water supplied to the crop, as it depends on other factors such as irrigation system efficiency.

Chapter 4: Assessment of Volume of Water Requirements and Irrigation Requirements by ISTAT Data

4.1 Data Preprocessing and Compatibility

Integration of crop model data with ISTAT data involves merging and combining the outputs of the crop model with the irrigation information provided by ISTAT.
This integration allows for a comprehensive analysis of crop water consumption, incorporating both simulated and observed data.

4.2 Data Processing

Cleaning and formatting both the crop model data and ISTAT data to ensure compatibility and consistency.
In this regard, the data of the irrigated area by different crops provided by ISTAT as vector shape files are converted to raster files with the same resolution as the crop model data using the QGIS tool.
The evapotranspiration model provides data in the EPSG:4326-WGS84 projection, while the ISTAT analysis of irrigated areas is conducted in the projection of EPSG:32632-WGS84/UTM Zone 32. To align these datasets, the raster layer of the model data is reprojected to match the projection of the irrigated area layer using the ”warp” (reproject) command in the QGIS tool.

4.3 Spatial and Temporal Alignment

Matching the spatial and temporal resolutions of the crop model data and ISTAT data facilitates meaningful comparisons. The crop model data spans five decades, from 1970 to 2019, while the ISTAT data used in this study pertains to the year 2010 and covers the entire Italy spatially.

To enable comparisons of climatic changes over the irrigation volume, average data over a ten-year span (2005-2014) and the reference year of 2010 are also analyzed.
To obtain the average value over the ten-year period, it is assumed that the irrigated area remains constant compared to the reference year of 2010.

Both the reference year and the ten-year span analysis are conducted for Italy as a whole and for the Piemonte region specifically.

4.4 Variable Harmonization

Achieving the data assimilation requires a careful alignment of variables or parameters measured by the crop model with those captured by ISTAT.
A challenge arises as the crop categories provided by ISTAT do not perfectly match the crop categorization of the crop model. Consequently, a process of simplification is necessary, involving the merging of two categories to derive a target category suitable for the study's objectives.

The crop model data utilized in this study typically represents a single growing season for all crops except wheat. For wheat, data is available for two separate sowing seasons, prompting separate analyses.
analysis is conducted twice for wheat, once for each sowing period, and it is assumed that the cultivated and irrigated area remains constant across both periods.

Below, the categorization of the two data sources is depicted in a table. In the reference dataset, ISTAT allocates different categories for the grain maze and green maize but since the crop model provides just one category for maize therefore in the table MAIZE is considered as the sum of the irrigated area by green maize and grain maize.

Table 4: Crop List Comparison

Utilized Crop Model Data	**Correspondent Crops by ISTAT**
maize_I	MAIZE: (grain maize + green maize)
rice_I	RICE
wheat_I	CEREAX : cereals for the production of grain (excluding maize and rise)
wheat_II	CEREAX: cereals for the production of grain (excluding maize and rise)
Average value of: others_annual_II & others_annual_I & others_annual_I	DRPUL: dried pulses
potato	POTAT: potato
sugar_beets	BEETS: sugar beet
The Average value of: others_annual_II & others_annual_I & others_annual_I	CROPTX: textile crops
potato	RAPETR : rape and turnip rape
sunflower	SUNFLO: sunflower
Average value of: others_annual_II & others_annual_I & others_annual_I	VEGFRO: fresh vegetables outdoor
fodder_grasses	TGRAOT : other temporary grass
Average value of: others_annual_II & others_annual_I & others_annual_I	ARLANO: other arable land crops
grapes	VINEY: vineyard
others_perennial	OLIV: olive plantation
citrus	CITRFR: citrus fruit
others_perennial	FRUIT: fruit plantations
others_perennial	NURSEPCROG: nurseries and other permanent crops
fodder_grasses	PGRAPM: permanent grassland, pastures, and meadows
The average value of others_annual_II & others_annual_I & others_annual_I	LSRC: land with short rotation coppices connected to the holding

4.5 Volume of Irrigation Requirement per Crop

The computation of the volume of Irrigation requirements and water requirements by crop in the grid is a critical aspect of this study, aimed at quantifying agricultural water usage within the study area. To accomplish this, we leverage raster layers depicting the irrigation requirements for each crop, alongside data detailing the area irrigated with different crops and irrigation systems. Through the multiplication of these values using the QGIS tool's raster calculator, we derive the volume of water consumption for each grid cell. Subsequently, the desired resolution is exported for further analysis.

This systematic approach is employed to estimate the volume of water usage for both the reference year and the average volume over the period from 2005 to 2014. By applying this method, we can calculate the volume of water usage for each crop during two distinct time spans, encompassing both the Piemonte region and the entirety of Italy. This comprehensive analysis allows us to discern the temporal variations in water consumption across different crops and geographic regions. So in each pixel:

$$V_{volume} = A_{Area} \cdot IR_{Depth} \tag{10}$$

As indicated in the above formula, V represents the volume of the irrigation requirement or the volume of the water requirement, A represents the irrigated area by each crop, and *IR* stands for the irrigation requirement or water requirement. This multiplication is applied to each pixel in order to obtain the irrigation and water requirements in each single grid for each crop. The area is given in hectares, and the volume of the irrigation or water requirements is given in mm/year; therefore, the volume is measured in cubic meters. *IR*, which is introduced here, is the same as ET_b or ET_C.

Table 5: Comparison of ETB values between different years in Italy (m^3)

Crop	**Italy ETB_2010** (m^3)	**pct 2010**	**Italy ETB_2005-2014** (m^3)	**pct 2004-2015**
whaet2	44931.92	0.0083	40682.05	0.007
whaet1	49239628.98	9.1076	54209870.91	8.750
Citrus	47219484.10	8.7339	65635771.78	10.594
sunflower	2214483.69	0.4096	2756157.06	0.445
SugarBeets	5932291.01	1.0973	13042898.75	2.105
MAIZE	45740275.78	8.4603	2756157.06	0.445
POTATO	3919701.78	0.7250	10382220.11	1.676
RICE	28634628.30	5.2964	28605723.71	4.617
vineyard(grapes)	61175015.08	11.3152	91379811.62	14.749
NURSEPCROG	994717.42	0.1840	1755717.20	0.283
LSRC	328213.60	0.0607	486819.89	0.079
ARLANO	5632725.41	1.0419	10068622.87	1.625
VEGFRO	93989317.27	17.3847	86408142.35	13.947
CROPTX	163591.08	0.0303	210144.36	0.034
DRPUL	1638135.74	0.3030	1794307.75	0.290
PGRAPM	5698310.18	1.0540	9138396.18	1.475
FRUIT	40439065.69	7.4798	62092559.50	10.022
OLIV	102614226.00	18.9800	114655360.16	18.506
TGRAOT	44413508.68	8.2149	63389358.42	10.231
RAPTER	612737.58	0.1133	756815.95	0.122
Total	540644989.3		619565537.7	

Table 6: Comparison of ETB values between different years in Piemonte (m^3)

Crop	Piemonte ETB_2010 (m^3)	pct 2010	Piemonte ETB_2005_2014 (m^3)	pct 2005-2014
whaet2	0.00	0.000	453.29	0.001
whaet1	470416.51	1.841	994137.75	2.818
Citrus	0.00	0.000	3.90	0.000
sunflower	27237.65	0.107	27170.55	0.077
SugarBeets	128317.28	0.502	219870.85	0.623
MAIZE	10117543.98	39.596	18157143.81	51.470
POTATO	141098.21	0.552	378212.76	1.072
RICE	12473849.67	48.817	10801899.78	30.620
vineyard(grapes)	322.21	0.001	1834.54	0.005
NURSEPCROG	31557.28	0.124	36685.66	0.104
LSRC	26004.03	0.102	71303.53	0.202
ARLANO	34991.82	0.137	143501.83	0.407
VEGFRO	250475.48	0.980	540523.07	1.532
CROPTX	288.70	0.001	854.39	0.002
DRPUL	31586.66	0.124	40690.48	0.115
PGRAPM	1026024.17	4.015	1645269.66	4.664
FRUIT	197835.03	0.774	529922.31	1.502
OLIV	230.77	0.001	1258.46	0.004
TGRAOT	503091.02	1.969	1578364.11	4.474
RAPTER	91197.50	0.357	107779.85	0.306
Total	2560700.22		35280274.88	

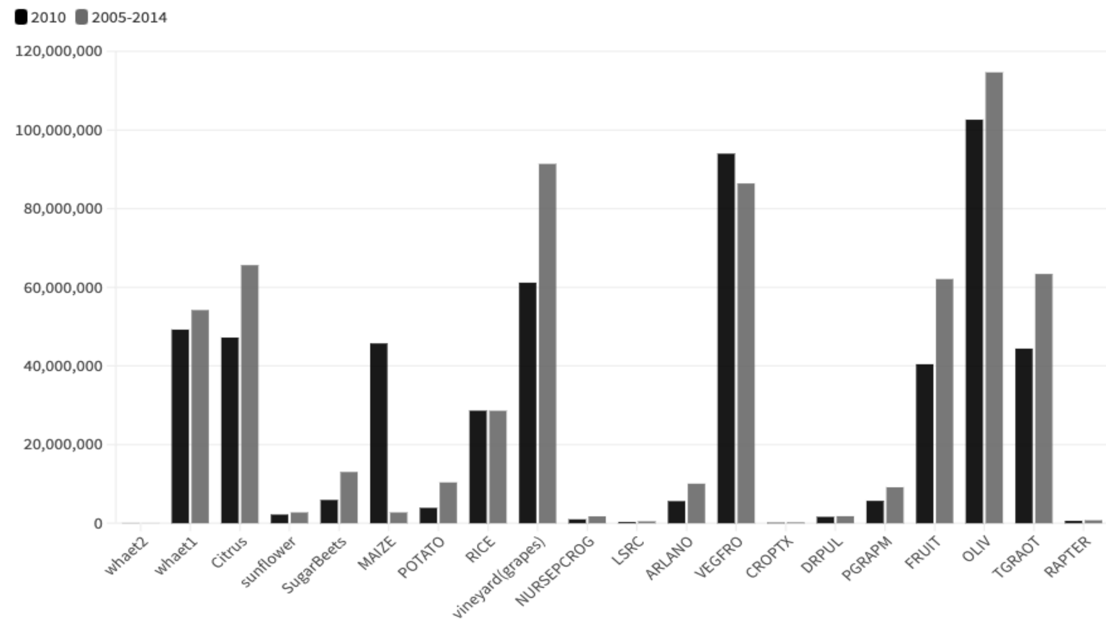

Figure 10: volume of irrigation per crop in Italy in 2010 and the average of 2005-2014

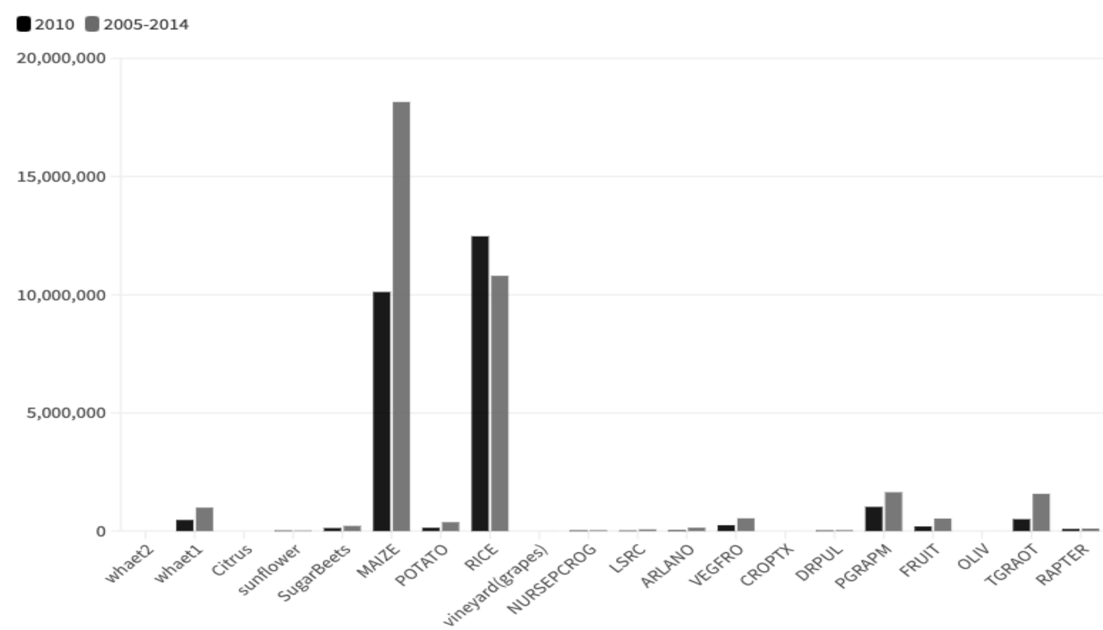

Figure 11: volume of irrigation per crop in Piemonte in 2010 and the average of 2005-2014

4.5.1 Examining Changes in Irrigation Volume Based on Crop-Area Irrigated in Italy

In terms of the reported data, the irrigation needs in Italy in 2010 show OLIV to be the crop with the highest irrigation requirement, followed by VEGFRO, vineyard (grapes), wheat1, and other crops, in descending order of water demand.

Looking at the average irrigation requirements for the period spanning 2005 to 2014, OLIV remains at the top, followed by vineyard (grapes), VEGFRO, Citrus, TGRAOT, FRUIT, wheat1, and other crops. This order reflects the historical water needs of these crops over the specified time frame.

Analysis of the data shows that the total irrigation requirements in Italy decreased in 2010 compared to the average value recorded between 2005 and 2014 the reduction is approximately 7.89×10^7 meter cube. While four crops experienced an increase in irrigation needs during 2010—namely wheat2, rice, VEGFRO, and MAIZE—the general trend for the other crops was a reduction in water demand during that reference year compared to the preceding average period.

The most significant reductions were observed in the vineyard (grapes), FRUIT, TGRAOT, Citrus, OLIV, Sugar Beets, and POTATO, Following this, smaller decreases were noted in descending order across the remaining crops.

Furthermore, a critical aspect to consider is the proportional percentage change, as it provides insight into the magnitude of shifts in irrigation requirements over time. The percentage change in irrigated volume indicates a decrease in the irrigation needs percentage for 2010 compared to the average from 2005 to 2014 for the vineyard(grapes), FRUIT, TGRAOT, Citrus, SugarBeets, POTATO, ARLANO, PGRAPM, NURSEPCROG, sunflower, LSRC, RAPTER, CROPTX. Conversely, for the rest of the crops, the trend is an increase in percentage change, indicating reduced water requirements during 2010 compared to the previous average period.

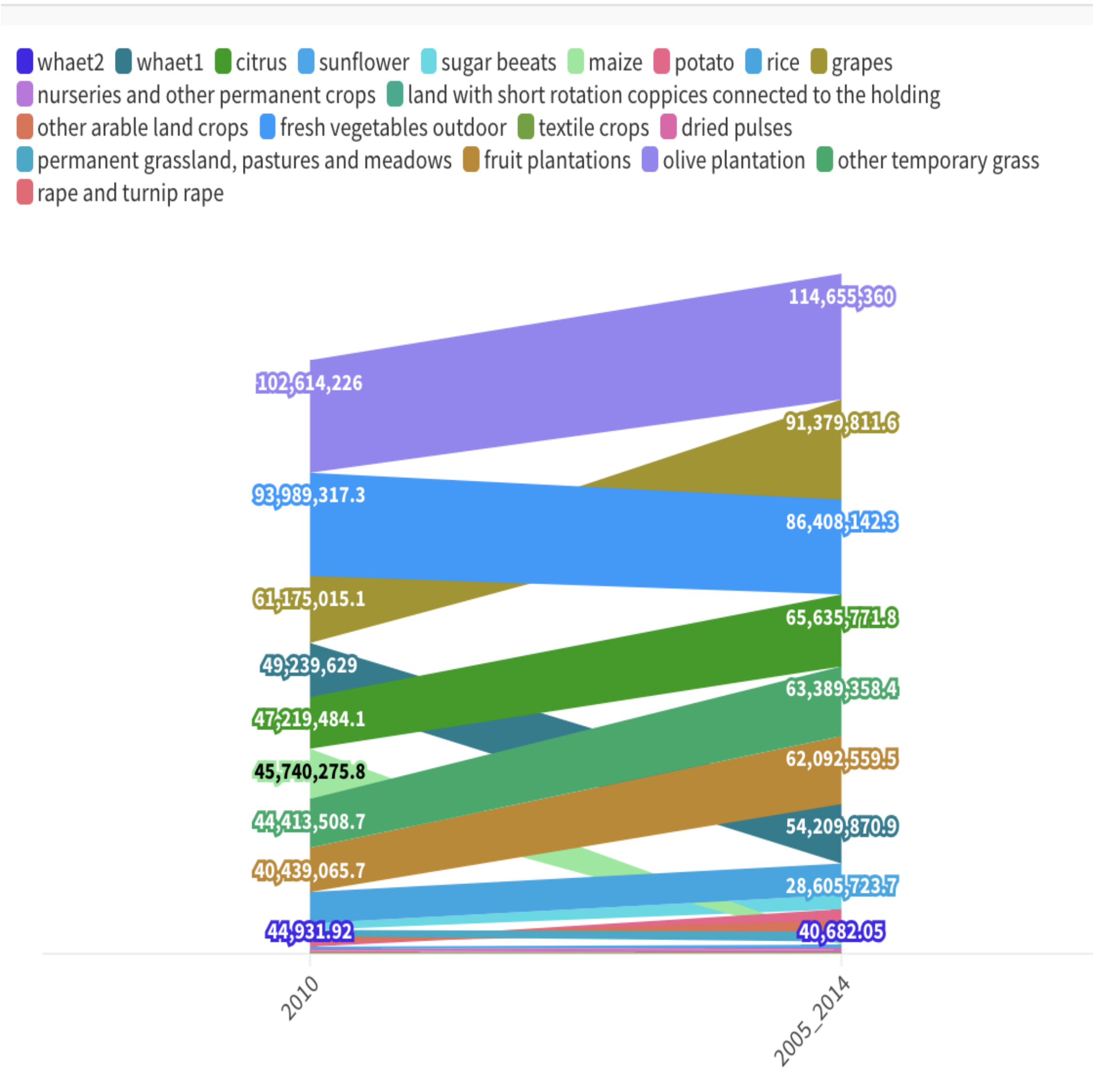

Figure 12: Evolution of water consumption by crops in Italy

4.5.2 Examining Changes in Irrigation Volume Based on Crop-Area Irrigated in Piemonte

In the Piemonte region, referring to the reported data, the irrigation needs in 2010 indicate that RICE has the highest requirement, followed by MAIZE, PGRAPM, TGRAOT, whaet1, VEGFRO, FRUIT, and POTATO in descending order of water demand.

Looking at the average irrigation requirements for the period spanning 2005 to 2014, MAIZE takes first place, followed by RICE, PGRAPM, TGRAOT, whaet1, VEGFRO, FRUIT.
This order reflects the historical water needs of these crops over the specified timeframe in descending order.

Analysis of the data shows that the total irrigation requirements in Piemonte decreased in 2010 compared to the average value recorded between 2005 and 2014. The reduction is approximately 3.27×10^7 cubic meters.
The trend is the same for all individual crops in Piemonte, with the irrigation requirement for all crops decreasing in 2010 with respect to the average amount from 2005 to 2014, except rice and sunflower, which experienced an increase.

The most significant reductions were observed in MAIZE, followed by TGRAOT, PGRAPM, whaet1, FRUIT, VEGFRO, POTATO, ARLANO, SugarBeets, LSRC, RAPTER, DRPUL, NURSEPCROG, vineyard(grapes), OLIV, CROPTX, whaet2, and Citrus (in descending order).

Furthermore, a critical aspect to consider is the proportional percentage change, as it provides insight into the magnitude of shifts in irrigation requirements over time. The percentage change in irrigated volume indicates an 11.8% decrease in the irrigation needs for MAIZE in 2010 compared to the average from 2005 to 2014. For RICE, there was an increment of 18.2%, and for the rest, the variation is less than 1%, which can be assumed as no change.

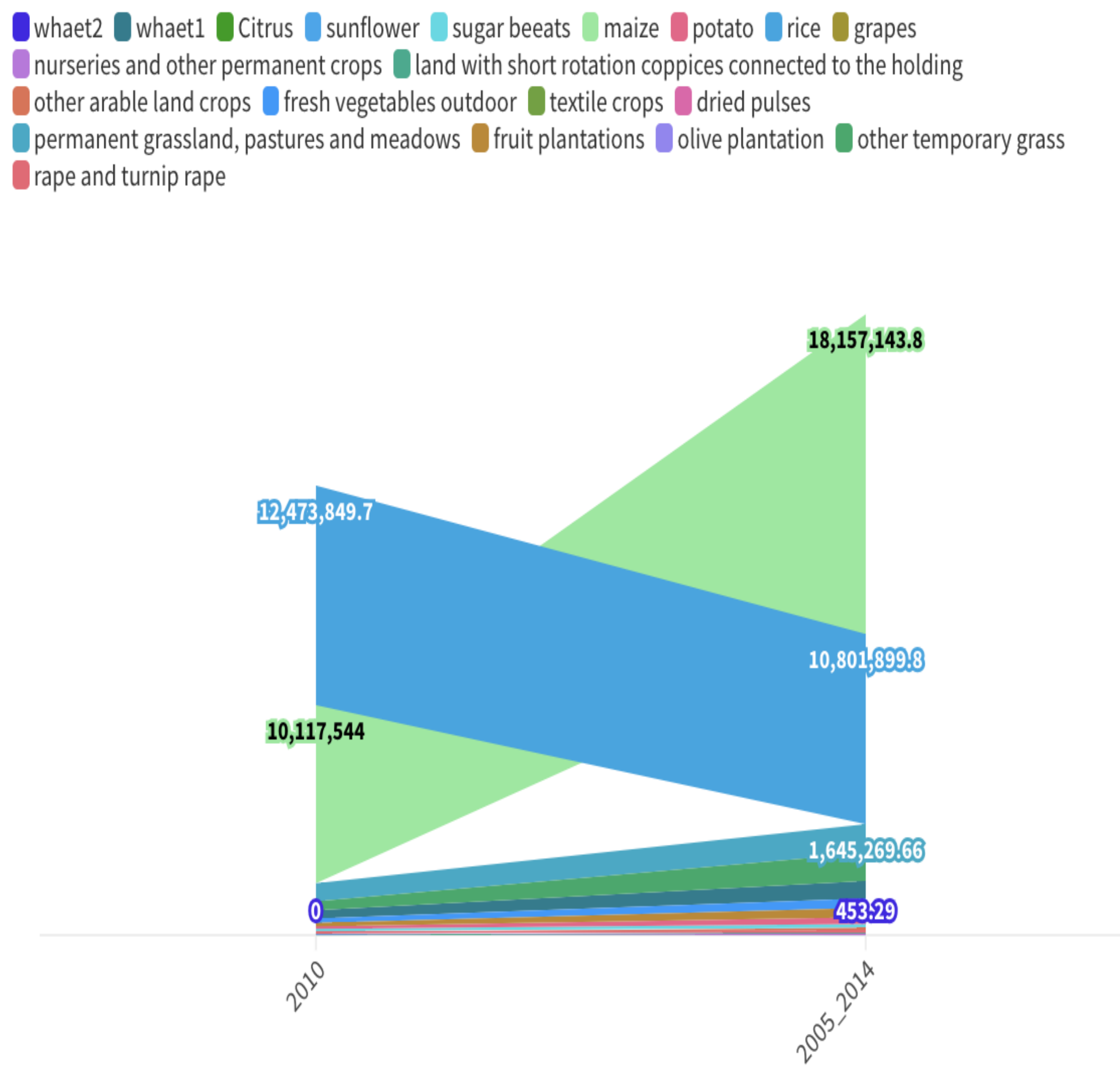

Figure 13: Evolution of water consumption by crops in Piemonte

The variations in irrigation observed between the two time spans primarily stem from differences in climate conditions. It's important to note that the area that is irrigated for each crop is assumed to remain constant temporarily. Therefore, any fluctuations in irrigation volumes can be attributed to changes in climate patterns over the specified periods. These climate-induced variations influence factors such as evapotranspiration rates, precipitation levels, and overall water availability.

The dispersion of consumed water is depicted on the map below for both Italy and Piemonte

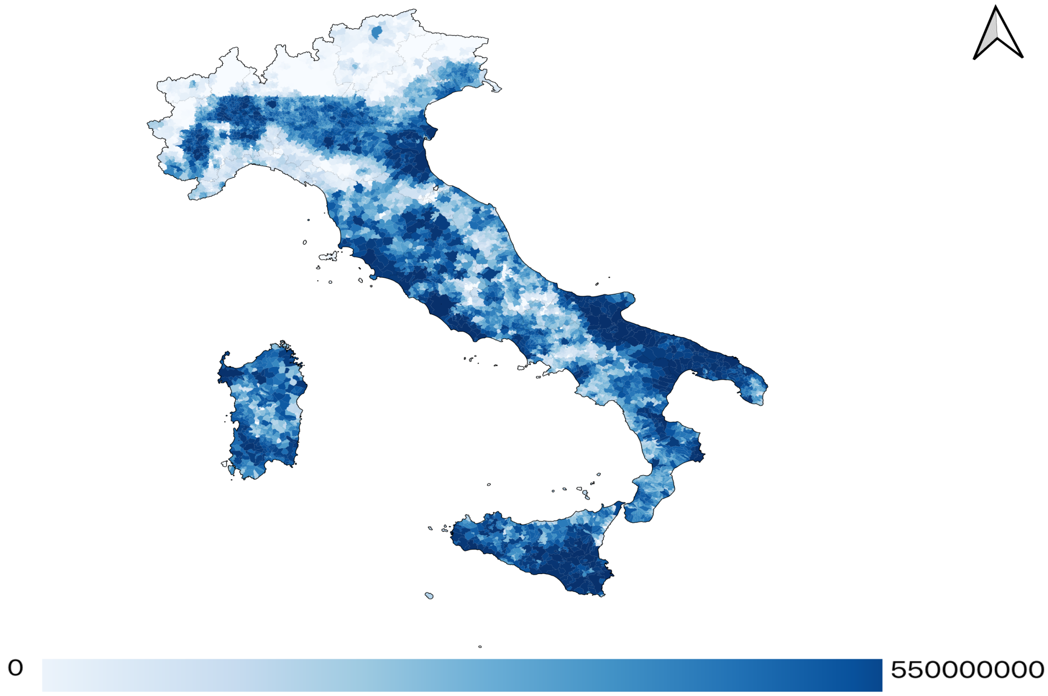

Figure 14: Volume of irrigation in Italy (2010)

Figure 15: Volume of irrigation in Piemonte (2010)

4.6 Volume of Irrigation Requirements per Irrigation System

In this study, an alternative methodology has been employed to determine the irrigation volume associated with various irrigation systems.
The initial step involves leveraging the data provided by ISTAT, which delineates the irrigated area attributed to different irrigation systems, a facet previously assessed in prior chapters.
Subsequently, by retrieving grid data of each irrigation system and aggregating the irrigation system data within grid cells, alongside utilizing grid data encompassing the total volume of water utilized in the study area, the volume of the irrigation requirement at the desired resolution is ascertained.

Table 7: Irrigation Volumes in Italy (m^3)

Irrigation System	**ETB_2010**	**ETB_2005_2014**
Aspersion (raindrop)	193932067	240906665.1
Flooding	19998745.43	21920312.52
Microirrigation	196346257.2	227866903.9
Other systems	24563334.01	27457320.66
Surface sliding and slide infiltration	70777828.47	81324584.92

Table 8: Irrigation Volumes in Piemonte(m^3)

Irrigation System	**ETB_2010**	**ETB_2005_2014**
Aspersion (raindrop)	3446922.226	5445696.804
Flooding	10148335.54	10177459.81
Microirrigation	297743.3557	522853.7368
Other systems	463147.4059	788611.1669
Surface sliding and slide infiltration	11349715.21	17027702.8

4.6.1 Examining Changes in Irrigation Volume Based on Different Irrigation Systems Across Italy

Microirrigation was the dominant irrigation System in Italy in 2010, utilizing approximately 196.35 million cubic meters in 2010 but in the average year of 2005-2014, the dominant irrigation System is aspersion(raindrop). The aspersion (Raindrop) System, while significant in both years, showed a slight decrease in usage from 2010 (193.93 million cubic meters) to the average for 2005-2014 (240.91 million cubic meters).
The flooding System exhibited relatively stable usage between 2010 (19.99 million cubic meters) and the average for 2005-2014 (21.92 million cubic meters), indicating consistent but perhaps less prevalent use compared to other systems.
Other systems demonstrated comparable usage levels between 2010 (24.56 million cubic meters) and the average for 2005-2014 (27.46 million cubic meters). The Surface Sliding and Slide Infiltration System showed a significant decrease in usage from 2010 (70.78 million cubic meters) to the average for 2005-2014 (81.32 million cubic meters), suggesting a notable shift or adoption of this System over the years.

4.6.2 Examining Changes in Irrigation Volume Based on Different Irrigation Systems Across Piemonte

The Surface sliding and slide infiltration System, while predominant in both 2010 and the average for 2005-2014, exhibited a decrease in usage from 2010 (11.35 million cubic meters) to the average for 2005-2014 (17.02 million cubic meters) in Piemonte.
The Aspersion(raindrop) System showed a notable decrease in usage from 2010 (3.45 million cubic meters) to the average for 2005-2014 (5.45 million cubic meters), suggesting a significant shift or increased adoption of this System. Microirrigation, Flooding, and Other systems demonstrated varying degrees of change in usage between 2010 and the average for 2005-2014, indicating potential fluctuations or adjustments in irrigation practices within the region.

4.7 Spatial Interpolation Management

It is necessary to check if the model's results match together and align in order to assess the performance and accuracy of the integrated model and ISTAT data outputs in representing real-world patterns and changes. In this study, this process is necessary. Checking the estimated irrigation volume data is necessary by comparing it with the total irrigation volume obtained through different irrigation systems. Discrepancies between the total irrigation volume by all crops and the sum of irrigation volume by different methods become apparent when analyzing the raster layer of irrigation volume for each crop in both Italy and the Piemonte region, for both the years 2010 and the average of 2005-2014.

The discrepancies in the results between the sum of the volumes of irrigated water between two different methods, by irrigation System and crop, in Italy for the year 2010 is 6.4‰, and in Italy for the average of 2005-2014 is 3.2‰. In the Piemonte region, the difference for the year 2010 is 0.6‰, and for the Piemonte the average of the year 2005-2014 is 3.7‰.

These discrepancies are primarily attributed to errors incurred during the rasterization process of irrigated areas.
To ascertain irrigation volume by different systems, the grid data of irrigated areas under various systems is divided by the grid data of all irrigated areas and then multiplied by the sum of irrigation volume by all crops in the reference year. The rasterization process introduces errors, such as the Mixed Pixel Problem and Topological Mismatch error.

Rasterizing vectors involves converting shape areas into a grid of pixels, which inherently includes errors.
The Mixed Pixel Problem arises when the cell size is larger than the feature being rasterized, leading to overestimation or underestimation of area. In this study, the vector features used are at the commune level, whereas the available raster data has a resolution of 0.0833, often resulting in pixel sizes larger than the commune size, exacerbating errors.

Additionally, the Topological Mismatch error occurs when the cell size is much smaller than the vector feature, resulting in jagged edges and loss of detail due to the grid's rigid structure. Resolution mismatch in raster calculations, such as raster multiplication, can also lead to errors.
An iterative processes were implemented in this project to align with the reference resolution and minimize errors. These validation efforts are essential for ensuring the reliability and accuracy of the model outputs, ultimately enhancing the credibility of the study's findings.

4.8 Comparison of Water Requirements and Irrigation Requirements

The crop model provided gridded data of the evapotranspiration for each crop, estimating the irrigated area given by ISTAT, which allows us to calculate how much water crops lose through evapotranspiration by crop.

By comparing the calculated water volume of evapotranspiration with the previously calculated volume of the water requirement by crop, one can gain insights about the values of the water supplied to the crop by rainfall, soil moisture, or other means except for direct irrigation.

The difference shows how much water comes from rainfall or soil moisture. If this difference is small for a crop, it means the crop is more at risk of water stress if it doesn't get enough irrigation. A smaller difference between the two values means that the most amount of crop water required is supplied by irrigation. It can be concluded that the importance of irrigation for crops increases by decreasing the difference between the two values and the role of irrigation becomes more important.

As illustrated in the figures below for Italy in the year 2010, the smallest difference is observed in CROPTX, indicating that a large portion of the crop's evapotranspiration must be supplied by irrigation. Following CROPTX are RAPTER, LSRC, DRPUL, sunflower, NURSEPCROG, POTATO, SugarBeets, RICE, and others with maize being last.

In the case of Italy for the average year of 2005–2014, CROPTX exhibits the highest difference between Irrigation requirements, and water requirements, suggesting that this crop requires a significant portion of its evapotranspiration water from irrigation. The subsequent crops in ascending order are RAPTER, LSRC, sunflower, DRPUL, NURSEPCROG, POTATO, and others.

For the region of Piemonte in the year 2010, CITRUS ranks first, followed by CROPTX, OLIV, vineyard (grapes), sunflower, SugarBeets, RAPTER, POTATO, and others, and in the last MAIZE, with maize receiving a significant portion of its evapotranspiration water from rainfall or other means apart from irrigation.

In the case of the Piemonte region for the average year of 2005-2014, CITRUS maintains the first position, followed by CROPTX, OLIV, vineyard (grapes), sunflower, SugarBeets, and others, and MAIZE as the last position.

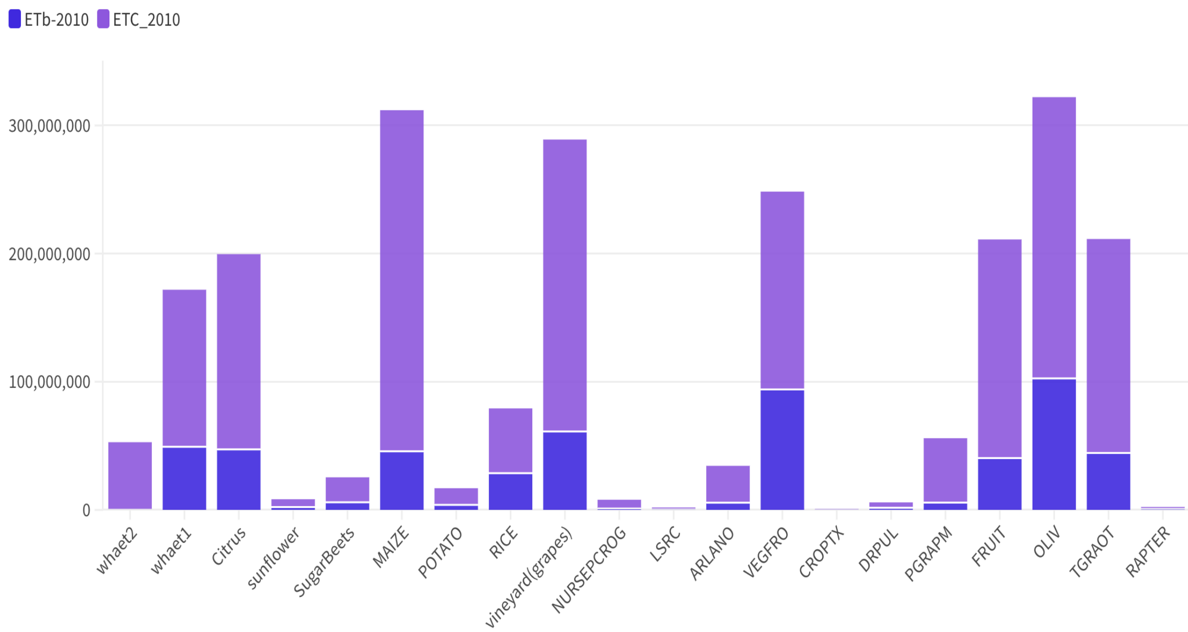

Figure 16: Comparison of Water Requirements and Irrigation Requirements in Italy in 2010

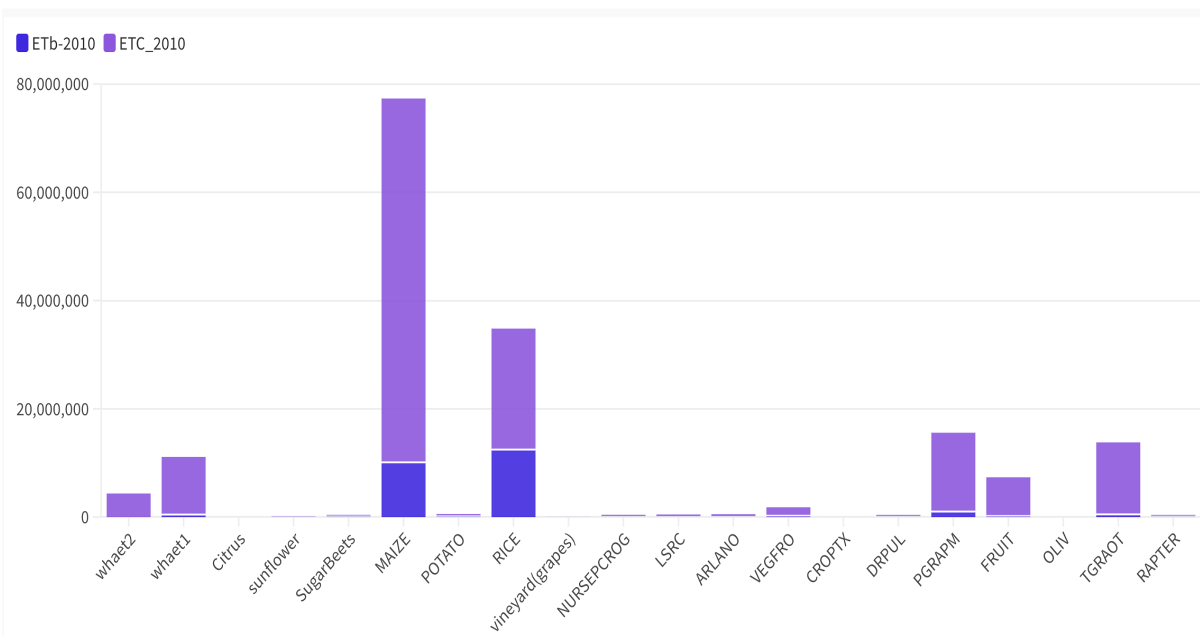

Figure 17: Comparison of Water Requirements and Irrigation Requirements in Piemonte in 2010

Chapter 5: Irrigation Systems and Efficiencies

Irrigation is defined as the controlled application of water for agricultural purposes through artificial systems to supplement natural rainfall.
Crop irrigation has a crucial role on a global scale, ensuring sufficient food production to meet the needs of the ever-growing population. Different irrigation techniques are utilized worldwide. When selecting the appropriate irrigation System, several key factors come into consideration:

The suitability of various irrigation Systems, including surface, sprinkler, or drip irrigation, depends mainly on the following factors:

- Natural Conditions: These comprise the kind of soil, the slope, the climate, and the availability and quality of water. Different irrigation systems are more appropriate depending on these natural factors.
- Type of Crop: All crops can benefit from surface irrigation, but high-value cash crops like fruit trees and vegetables are usually best served by drip and sprinkler systems. Close-growing crops like rice might not be a good fit for drip irrigation, but it works well for individual plants or trees and row crops like vegetables and sugarcane.
- Type of Technology: Surface irrigation is simpler than drip and sprinkler irrigation from a technical standpoint, but The equipment needed for sprinkler and drip irrigation techniques costs extra money per hectare.
- Previous Experience with Irrigation: The choice of irrigation system may also depend on the irrigation tradition within the region or country. Introducing a new system may lead to unexpected complications, and farmers may be reluctant to adopt it due to concerns about equipment servicing and related costs.
- Required Labor Inputs: Compared to sprinkler or drip irrigation, surface irrigation frequently demands a larger human resources input during installation, operation, and maintenance. For surface irrigation systems to function well, precise field leveling, consistent upkeep, and a high degree of farmer organization are necessary.
- Costs and Benefits: Before selecting an irrigation system, an assessment should be made of the costs and benefits of the available options. This includes considering construction, installation, operation, and maintenance costs per hectare. It's essential to weigh these costs against the potential benefits of increased crop yields and water efficiency.[5]

Based on the ISTAT data, the irrigation systems in Italy include Aspersion, Flooding, micro irrigation, surface sliding, slide infiltration, and other systems. Not all water taken from a source (such as a river or well) reaches the root zone of the plants. Some of it is lost during transport through canals and in the fields. the water loss can be divided into two categories Conveyance efficiency and Field application efficiency.

Irrigation efficiency can be introduced in two categories:

5.1 Conveyance Efficiency (ec)

This shows how efficient the water transport through the irrigation system is.

The means of water loss in canals include:

- Evaporation from the water surface
- Deep percolation of soil layers underneath the canals
- Seepage through the bunds of the canals
- Overtopping of the bunds
- Bund breaks
- Runoff in the drain
- Rat holes in the canal bunds

5.2 Field application efficiency (ea)

This indicates the efficiency of water application within the field. field application efficiency includes:

- Surface runoff, leading to water ending up in the drain
- Deep percolation to soil layers below the root zone

For this study, only field application efficiency is considered. The following irrigation efficiencies, as reported by FAO, are used:

- Surface irrigation (border, furrow, basin): 60%
- Sprinkler irrigation: 75%
- Drip irrigation: 90%

Although there are slight terminology differences between ISTAT and FAO, for this study:

- Surface irrigation (border, furrow, basin) is assumed to be equivalent to surface sliding, slide infiltration, and flooding.
- Sprinkler irrigation is assumed to be equivalent to aspersion (raindrop).
- Drip irrigation is assumed to be equivalent to micro-irrigation.

For other systems, the average value of efficiencies is considered. Using the provided efficiencies, it's feasible to estimate the amount of water withdrawn from the source for irrigation purposes. The volume of water used by different irrigation systems has already been estimated for two time spans which are 2010 and the average value of 2005-2014, spatially for both the Piemonte region and Italy.

By dividing the volume of irrigation by the corresponding efficiency, the actual amount of water required to be withdrawn from the source for each irrigation system can be estimated. This calculation provides valuable insight into the actual water demand for agricultural irrigation practices.

Table 9: Water Withdrawal (m^3) in Italy

Irrigation System	Italy_Etb_2010	Italy_Etb_2005_2014
Aspersion (Raindrop)	258576089	321208886.6
Flooding	33331242.26	36533854.09
Microirrigation	218162507.7	253185448
Other Systems	32751112.09	36609760.86
Surface Sliding and Slide Infiltration	117963047.2	135540974.7

Table 10: Water Withdrawal (m^3) in Piemonte

Irrigation System	Piemonte_Etb_2010	Piemonte_Etb_2005_2014
Aspersion (Raindrop)	4,595,896.277	7,260,929.048
Flooding	16,913,892.48	16,962,432.93
Microirrigation	330,825.9519	580,948.5914
Other Systems	617,529.8739	1,051,481.534
Surface Sliding and Slide Infiltration	18,916,191.9	28,379,504.67

According to the reported numbers, water withdrawal in Italy specifically in the Piemonte region decreased in 2010 compared to the average values from 2005 to 2014. The situation in Piemonte was notably better than the national average, with a decrease of 23.7% in the region compared to roughly 15.6% for Italy as a whole.
When examining irrigation systems individually, it becomes evident that there was a decrease in the volume of irrigated water across all systems in 2010 compared to the 2005-2014 average, both in Italy and in the Piemonte region.

In Italy, the most significant decrease was observed in Aspersion (raindrop) irrigation, which saw a reduction of 19.5%. The remaining systems experienced a decrease of 8.7% for Flooding, 13.8% for Microirrigation, 10.5% for Other systems, and 13% for Surface Sliding and Slide Infiltration.

In Piemonte, the largest decrease was seen in Microirrigation, with a reduction of 43%. The other methods experienced decreases of 36.7% for Aspersion (raindrop), 0.3% for Flooding, 41.3% for Other systems, and approximately 33.34% for Surface Sliding and Slide Infiltration.

This analysis employs a method of proportional percentage change to compare the increment or decrement of water withdrawal volume in Italy over two distinct periods.

Proportional percentage change assesses the relative change in withdrawal volume by expressing it as a percentage of the change relative to a reference year.
By utilizing this System, we can effectively gauge the significance of shifts in water withdrawal volume over time, irrespective of the initial volume. This approach facilitates the identification of trends and the evaluation of policy effectiveness or resource management strategies.

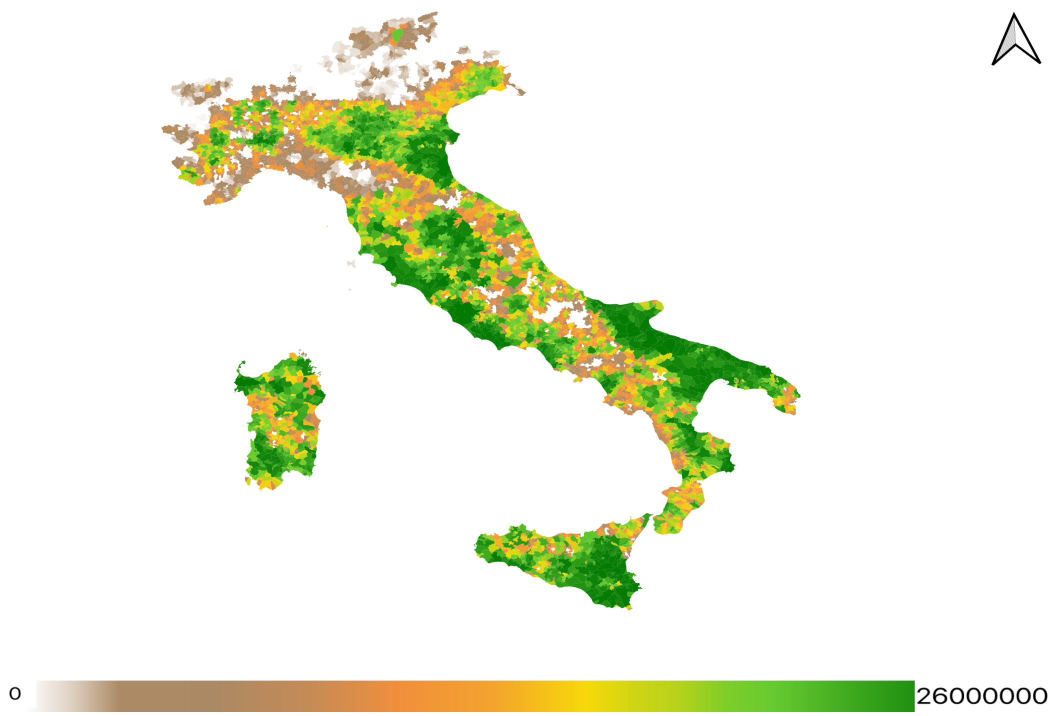

Figure 18: Volume of water withdrawal in Italy by Aspersion system

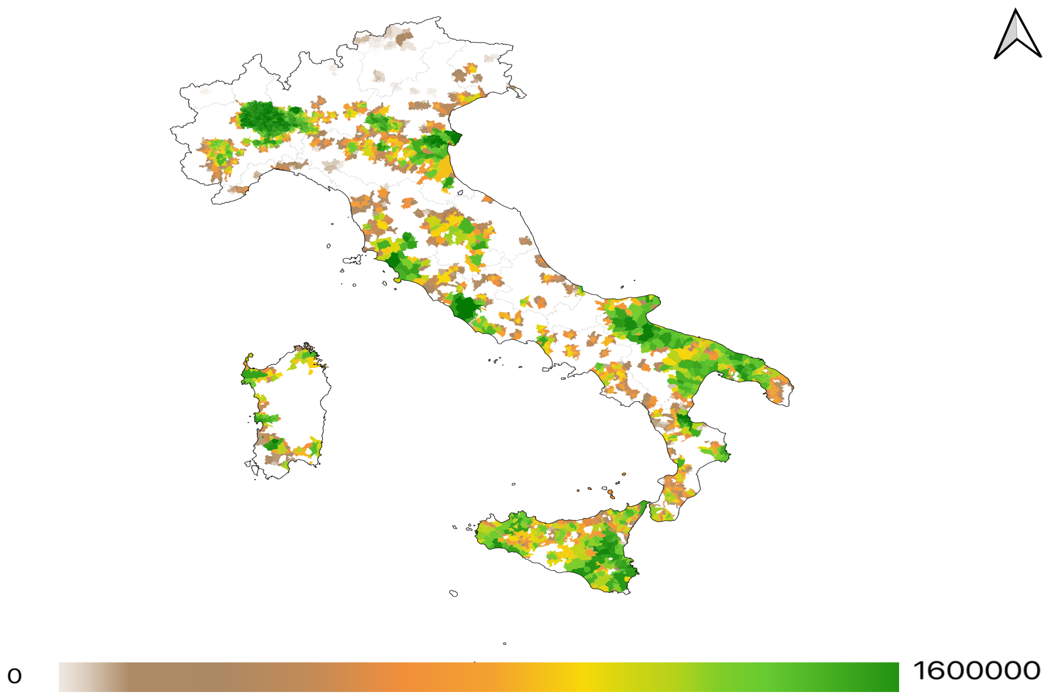

Figure 19: Volume of water withdrawal in Italy in 2010 by FlOO system

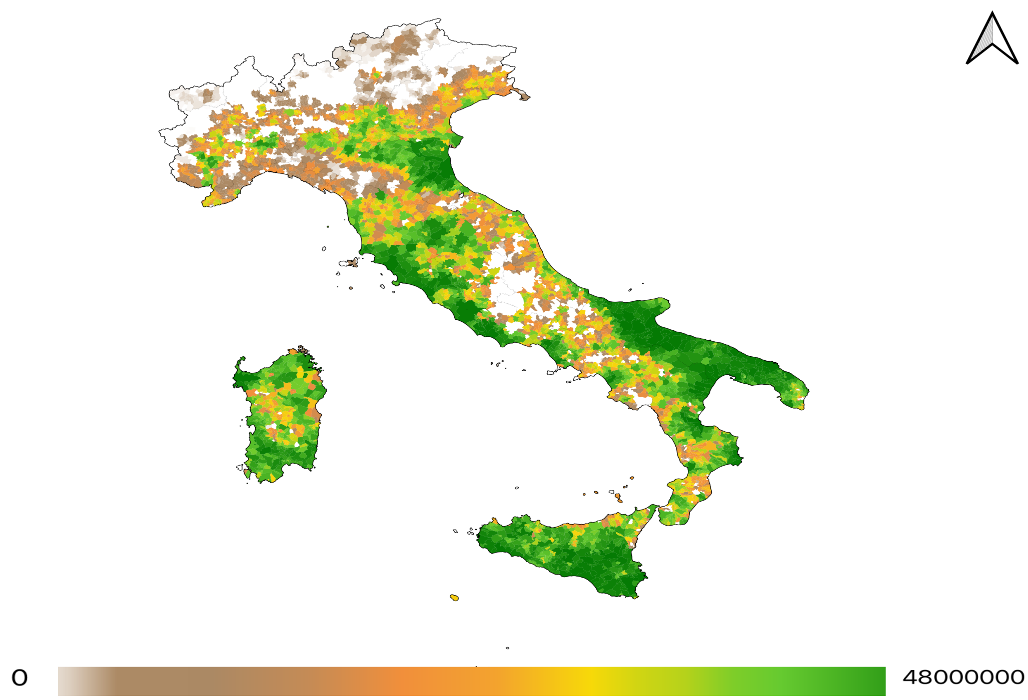

Figure 20: Volume of water withdrawal in Italy in 2010 by MICR system

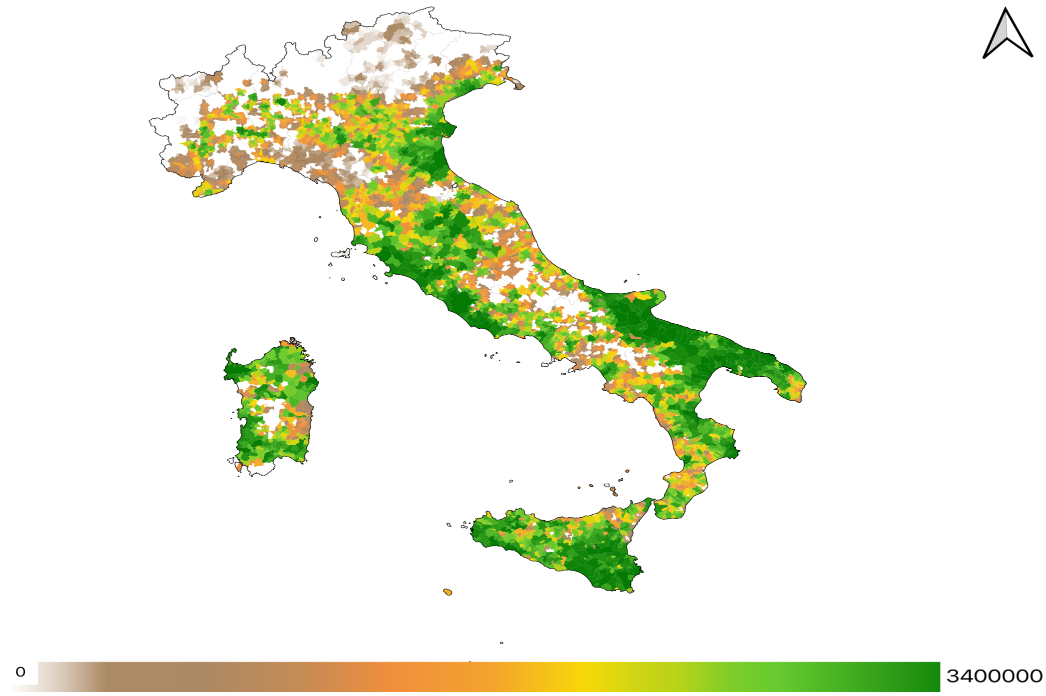

Figure 21: Volume of water withdrawal in Italy in 2010 by OTSY system

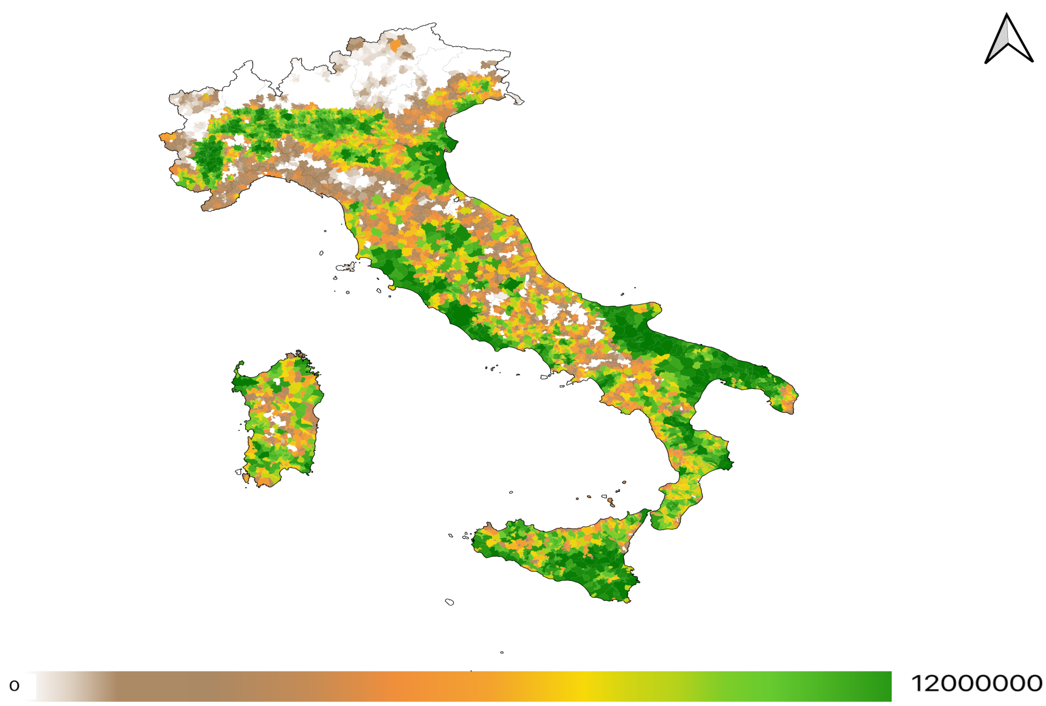

Figure 22: Volume of water withdrawal in Italy in 2010 by SSSI system

The spatial distribution of irrigation systems in the study area is depicted, revealing a lack of uniformity and significant variance based on irrigation Systems Predominantly, the irrigated areas are concentrated in the southeast of Italy. Across all irrigation systems, there is a substantial volume of water withdrawal occurring in these southeastern regions.

Upon examining the visualized maps, it becomes evident that the volume of water withdrawal is consistently highest in the region of *Puglia* for all irrigation systems. Conversely, the lowest amounts of water withdrawal are observed in the northeast of Italy, specifically in the regions of *Friuli-Venezia Giulia* and *Trentino-Alto Adige/Südtirol*. Additionally, the northwest region of *Valle d'Aosta* exhibits comparatively low volumes of irrigation

To gain a clearer insight into the temporal fluctuations of water withdrawal, we've visually depicted the absolute volume changes in a spider chart below. This chart provides an additional viewpoint, facilitating comparisons of actual water withdrawal volumes across defined time intervals. By combining these analyses, we obtain a comprehensive understanding of water withdrawal dynamics in Italy and the Piemonte region, encompassing both relative shifts and absolute changes. As it is visible the volume of the water withdrawal has decreased in 2010 with respect to the average value of 2005-2014 both in Italy and Piemonte.

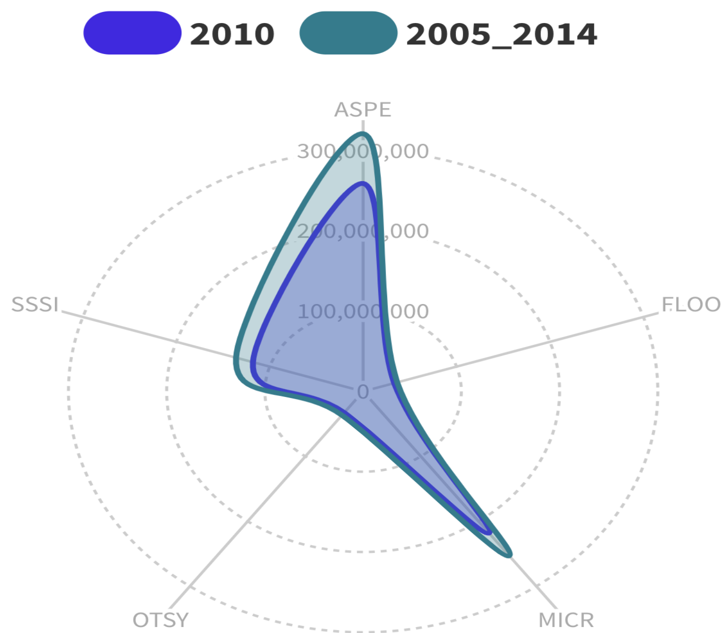

Figure 23: Volume of the water withdrawal in Italy

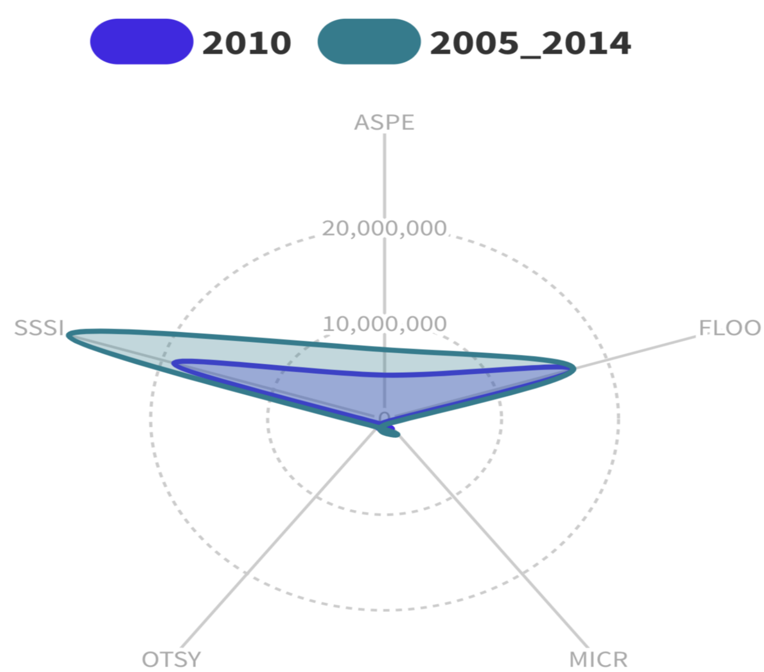

Figure 24: Volume of the water withdrawal in Piemonte

Chapter 6: Conclusion

The approach to dealing with water problems has evolved throughout history, leading to a shift in the paradigm of water resource management. Before World War II, the approach was solely focused on engineering. In the post-World War II era, it evolved to include both engineering and economic considerations. By the early 1970s, it had expanded further to encompass engineering, economic, and environmental factors. In the early 1980s, it incorporated social aspects and stakeholder participation alongside engineering, economic, and environmental considerations. By the mid-1990s, this approach involved NGO involvement and public acceptance, in addition to the aforementioned factors.

Over time, humanity's perception of water problems has evolved, recognizing the finite nature of water resources. The problem-solving approach shifted to consider not only the supply side but also the demand side.

In the past, many problems were tackled by building dams or transferring interbasin water, which remains common in developing countries. However, a deeper understanding of the issue reveals that addressing the demand side of the problem is crucial. This understanding has led to the development of water management techniques and strategies.

In this regard, two distinct frameworks have been developed:

1. **Sustainable Development Goals (SDGs)**

   The 2030 agenda for sustainable development, adopted by United Nations members, aims to achieve peace and prosperity for people and the planet. The SDGs were developed primarily as a response to the recognition of the interconnectedness of global challenges. The agenda includes 17 goals, such as No Poverty (SDG 1), Zero Hunger (SDG 2), Good Health and Well-being (SDG 3), Quality Education (SDG 4), Gender Equality (SDG 5), Clean Water and Sanitation (SDG 6), Affordable and Clean Energy (SDG 7), Decent Work and Economic Growth (SDG 8), Industry, Innovation, and Infrastructure (SDG 9), Reduced Inequalities (SDG 10), Sustainable Cities and Communities (SDG 11), Responsible Consumption and Production (SDG 12), Climate Action (SDG 13), Life Below Water (SDG 14), Life on Land (SDG 15), Peace, Justice, and Strong Institutions (SDG 16), and Partnerships for the Goals (SDG 17). The SDGs provide a comprehensive framework for tackling global challenges, involving governments, civil society organizations, and diverse communities in their development and implementation.

2. **Shared Socioeconomic Pathways (SSPs)**

   Developed by the Intergovernmental Panel on Climate Change (IPCC), SSPs represent future socioeconomic projections. They assess how socioeconomic factors may influence future scenarios.

The differences between these two frameworks lie in their focus and orientation. SDGs set goals to be achieved, while SSPs offer scenarios or projections showing how the world might evolve. SDGs primarily focus on political aspects and action-oriented solutions, while SSPs are more scientifically oriented and take a broader perspective on the problem. In essence, SDGs provide the ”what” we want to achieve, while SSPs explore the route that should be taken to reach the goal. By understanding these initiatives, the results and context of this study can be utilized to achieve these goals.

To overcome the issues caused by climatic variability, this study emphasizes the need for proactive actions and educated planning. It also offers important insights into the water consumption within Italy’s agricultural sector. Through an examination of detailed data about patterns of water usage, it sheds insight into the difficulties and prospects associated with sustainable water resource management in Italy’s agricultural sector.

Results from the study indicate that raindrop (aspersion) and micro-irrigation systems extracted the largest amount of water for irrigation across Italy in 2010, comprising 72% of all withdrawn water, with aspersion including almost 40% and micro-irrigation consisting of 33%. However, inefficiencies in these Systems suggest that approximately 25% of the water extracted is wasted, indicating potential for improvement.

In the Piemonte region, the surface sliding and slide infiltration system encompassed the largest share of withdrawn water at 45%, followed by flooding at nearly 40%. Despite their dominance, the efficiency of these Systems suggests a 40% loss or waste in the 85% of water withdrawal in Piemonte, highlighting a significant issue compared to the national average.

The study concludes that reducing water loss through changes in irrigation Systems and the adoption of efficient irrigation technologies is essential for enhancing agricultural productivity and sustainability. It emphasizes the need to recognize water as an economic good and advocates for proactive measures to minimize water wastage, thereby facilitating increased agricultural production.

The study envisions the development of sustainable agricultural practices and water management strategies through cooperative efforts and evidence-driven interventions to ensure the appropriate management of water resources while enhancing resilience and adaptability to changing environmental conditions.

A suggestion for further study could be the economic aspect of water resource management in food production and agriculture, aiming to maximize productivity through efficient water usage.
Additionally, assessing the food value chain within this context using the SAFA (Sustainability Assessment of Food and Agriculture) tool could be beneficial. The SAFA tool serves as an initiative to evaluate sustainability along food and agriculture value chains, involving steps such as mapping, contextualizing, identifying indicators, and reporting.

SAFA offers indicators across various themes, including governance, environment, social, and economic, to assess sustainability. It is important to remember that these indicators are mostly descriptive and that using them successfully necessitates a thorough understanding of the research field.

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Appendix I - Validation of GMIA Spatial Data for Irrigated Area

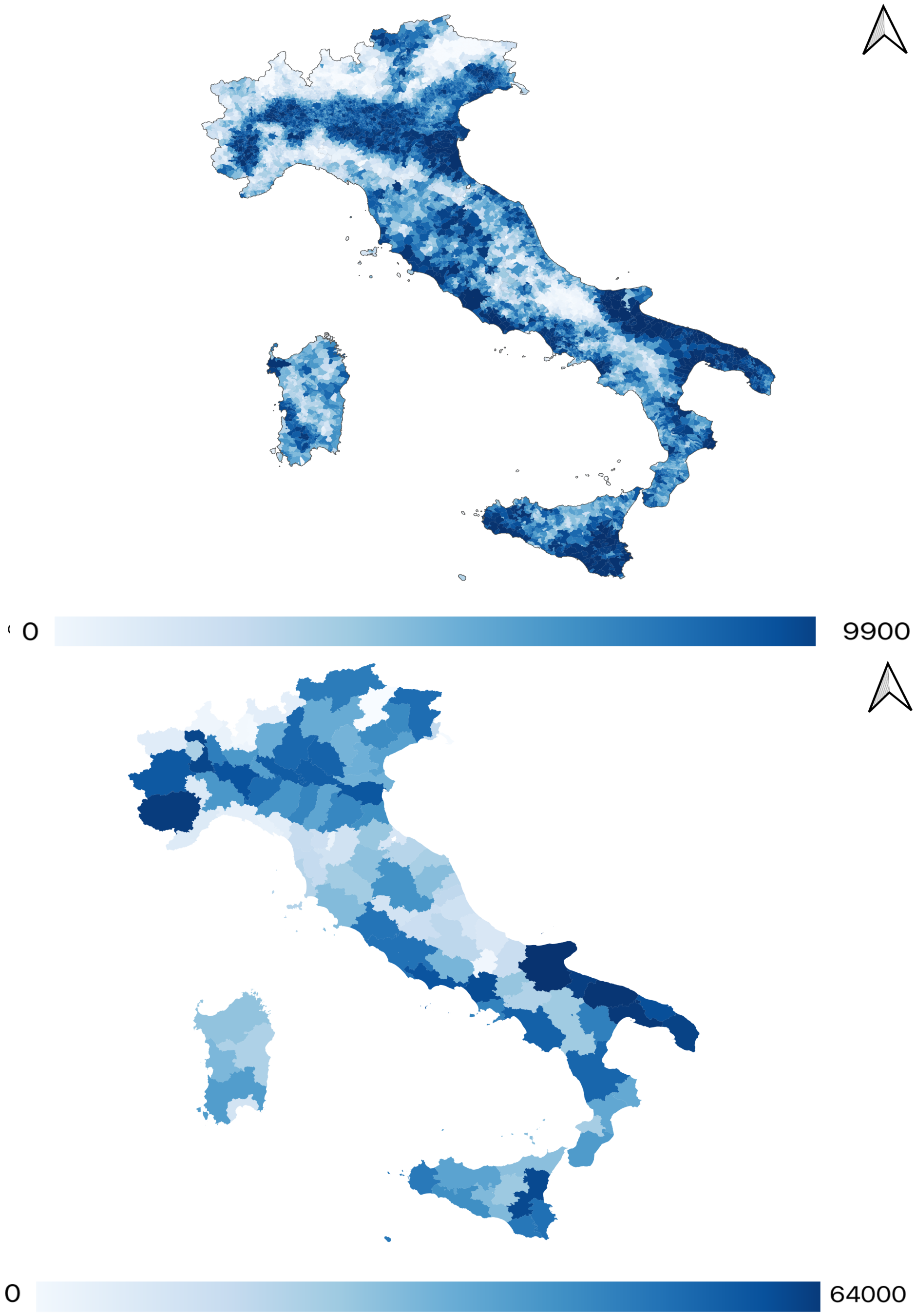

Figure 25: All the Irrigated Area in Italy by GMIA in the province and commune level

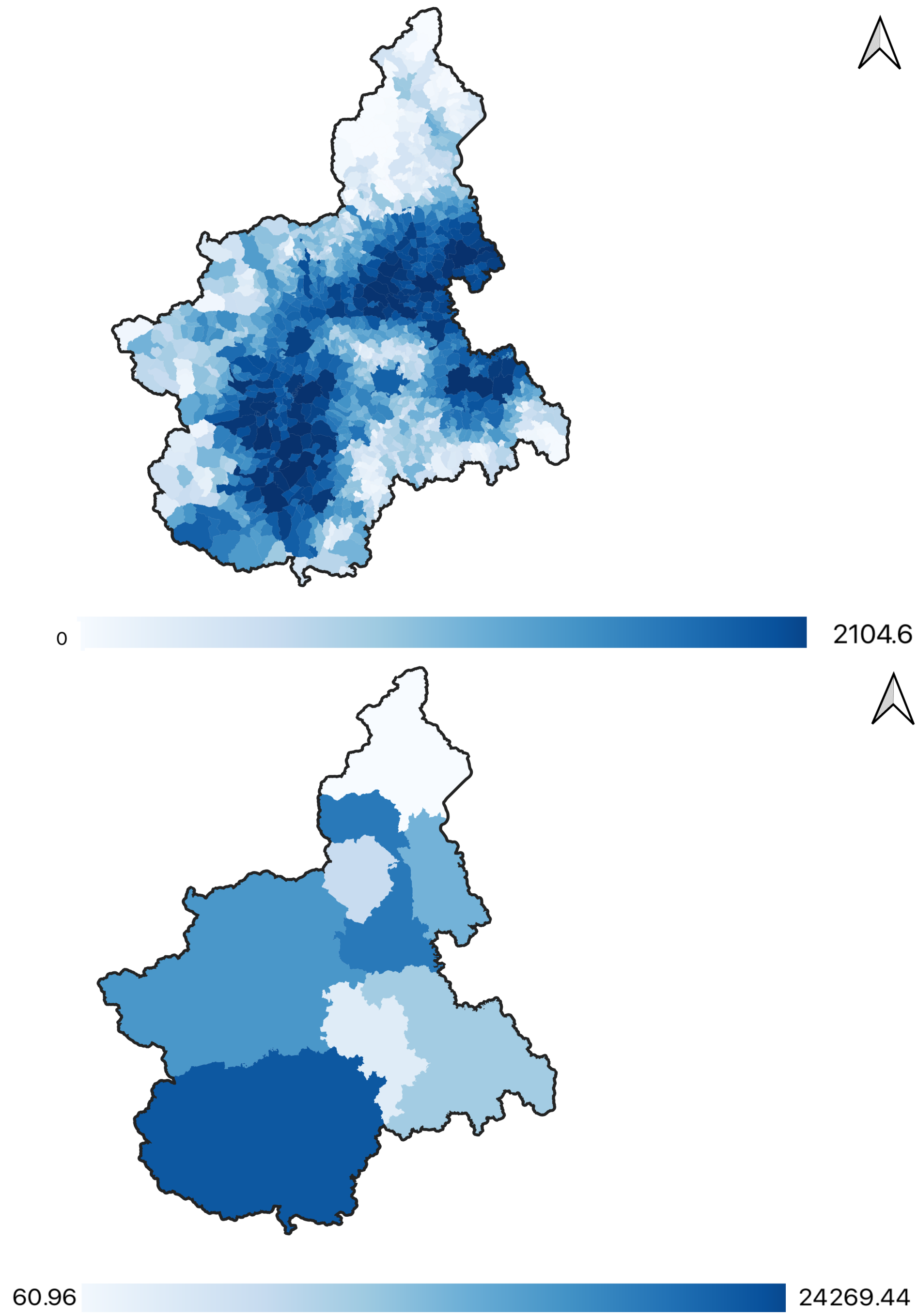

Figure 26: All the Irrigated Area in Piemonte by GMIA in province and commune level

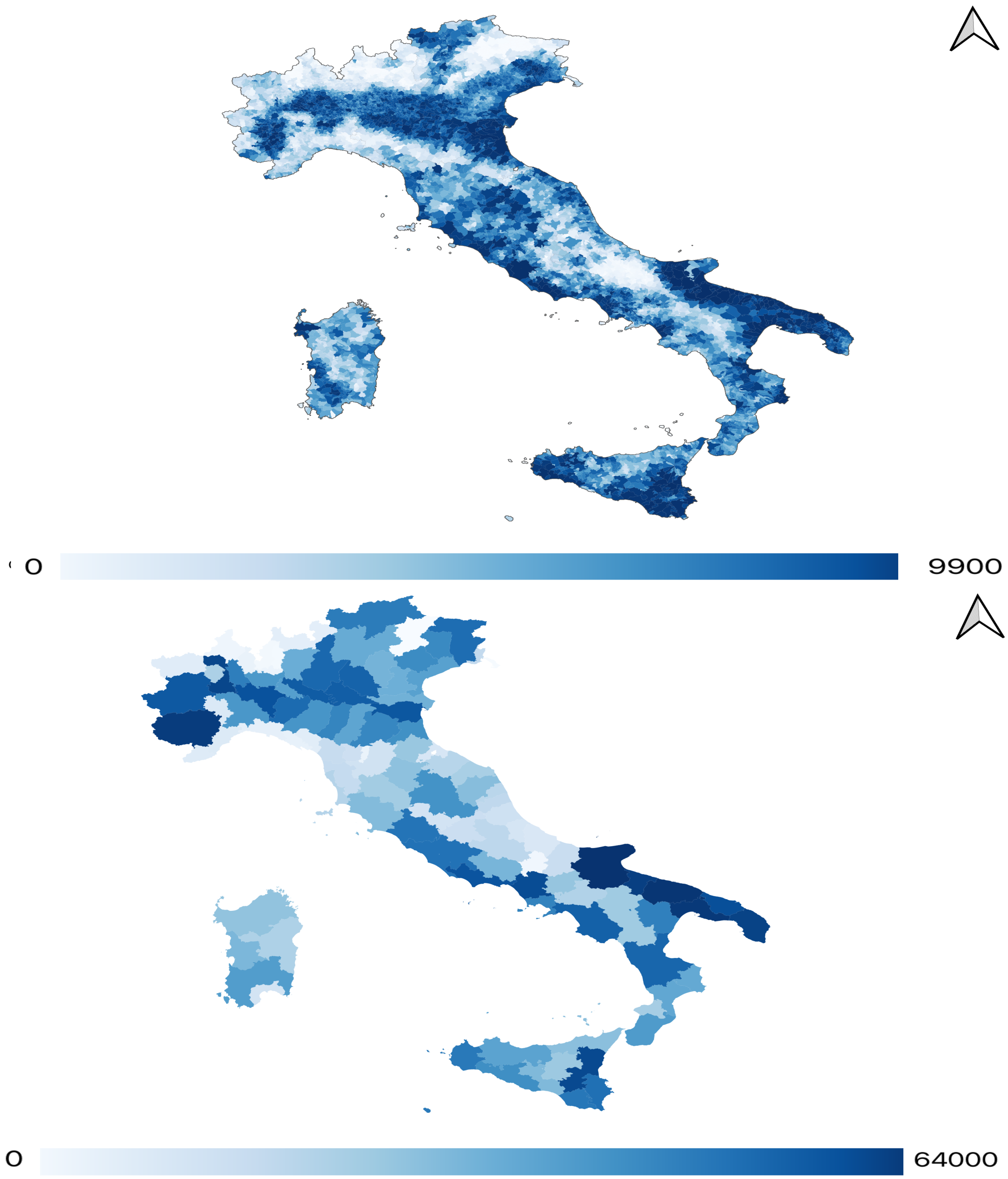

Figure 27: Area Irrigated by groundwater in Italy by GMIA in province and commune level

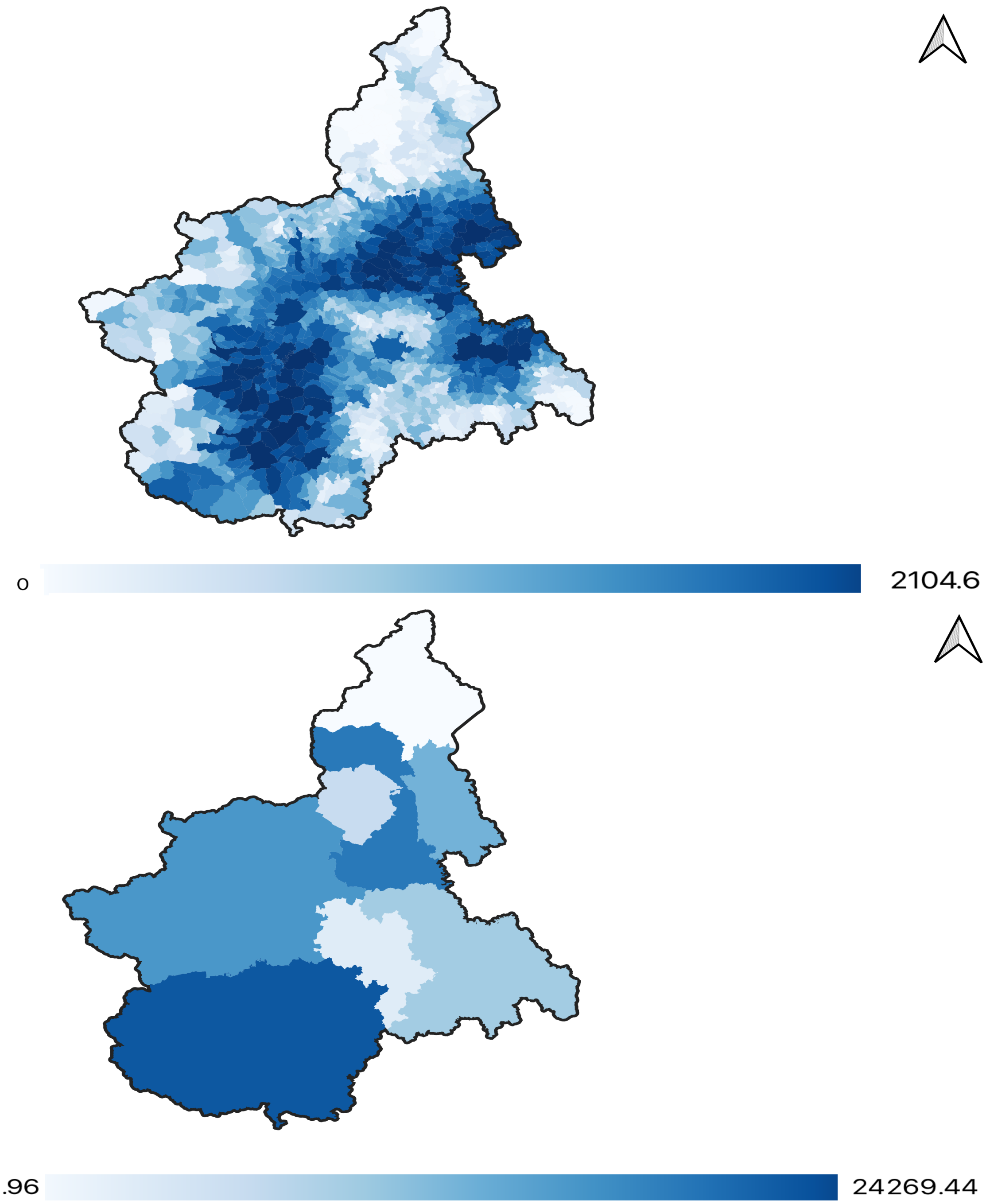

Figure 28: Area Irrigated by groundwater in Piemonte by GMIA in province and commune level

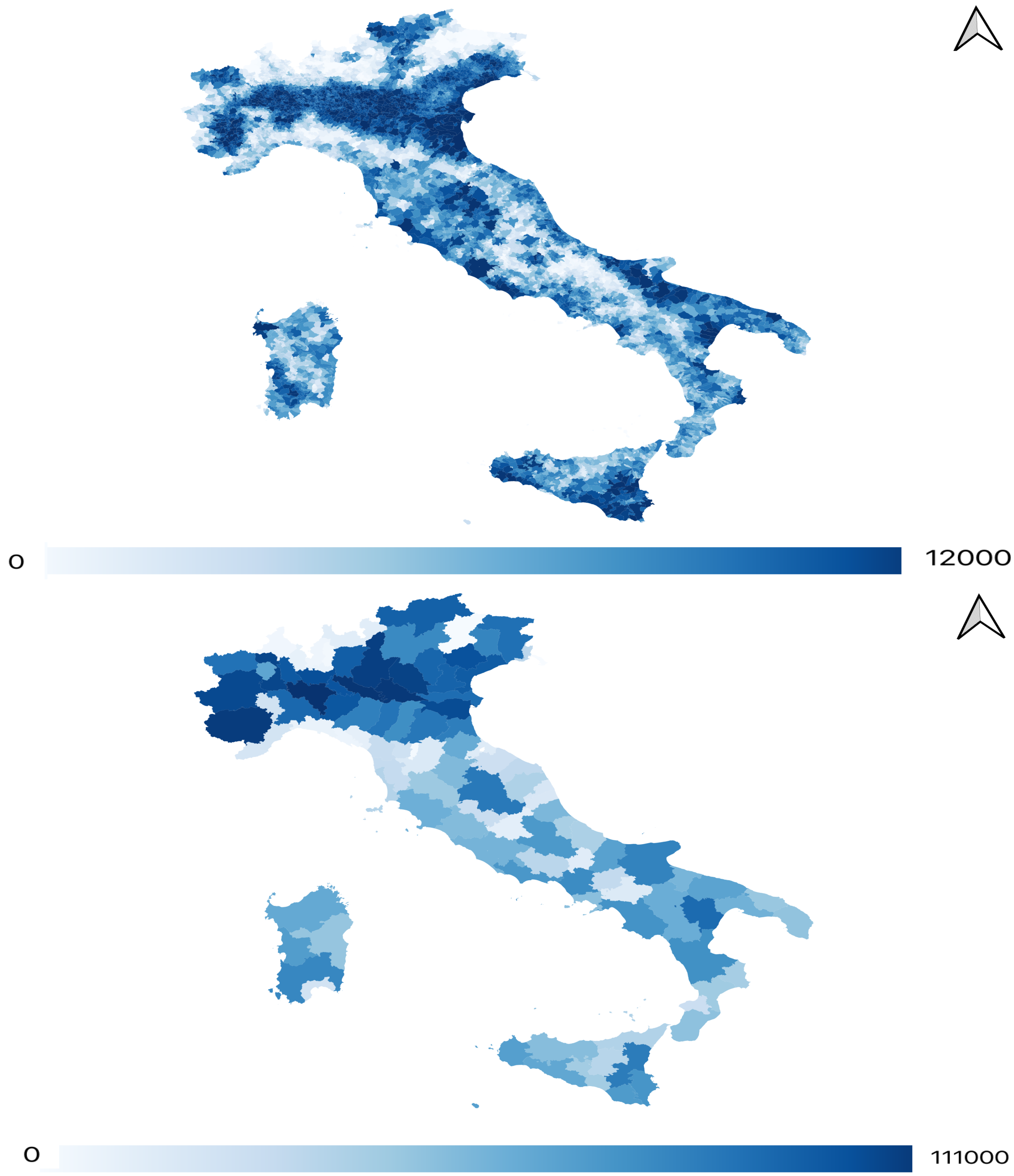

Figure 29: Area Irrigated by surface water in Italy by GMIA in province and commune level

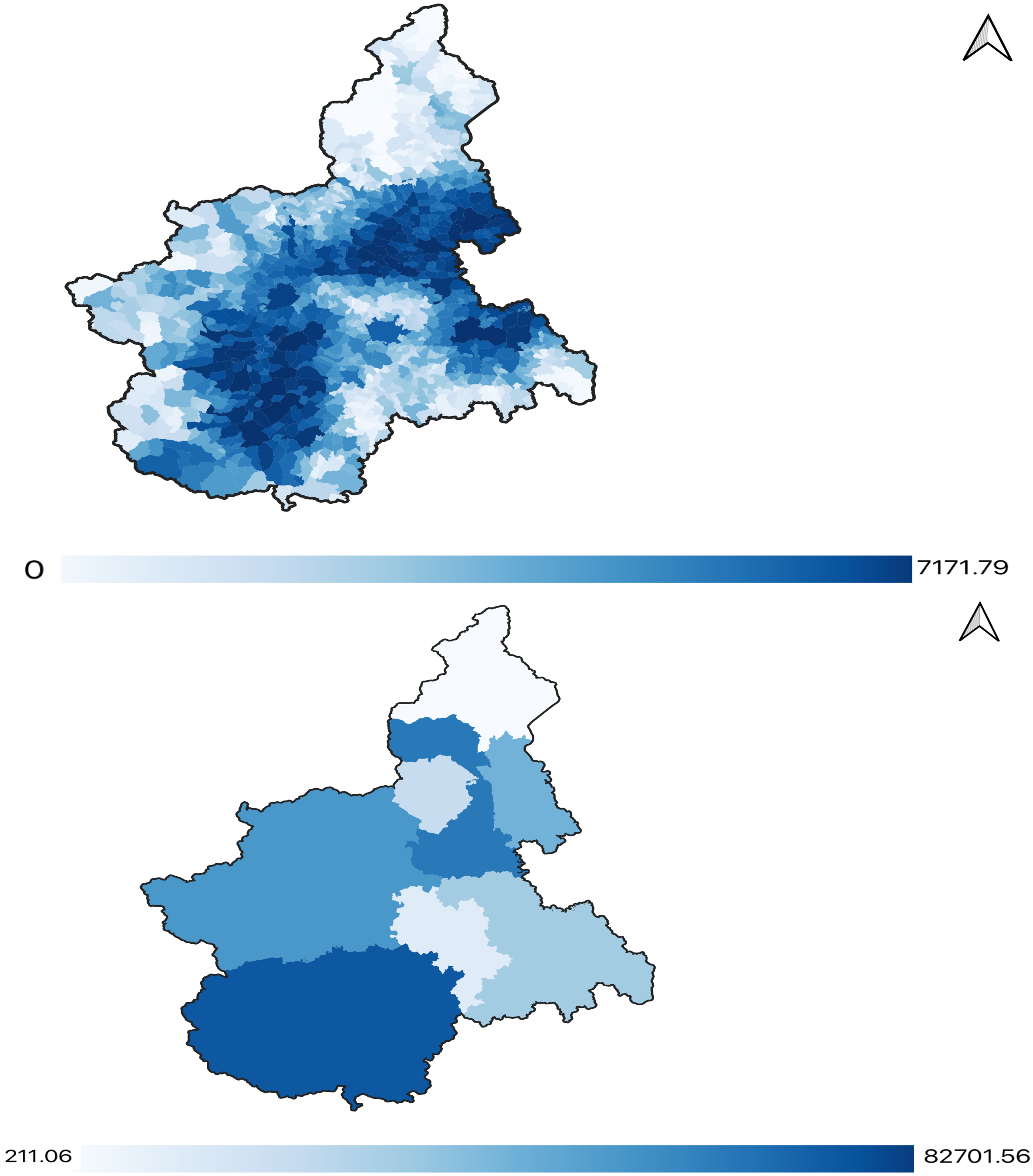

Figure 30: Area Irrigated by surface water in Piemonte by GMIA in province and commune level

Appendix II - Representation of ISTAT Spatial Data for Irrigated Area

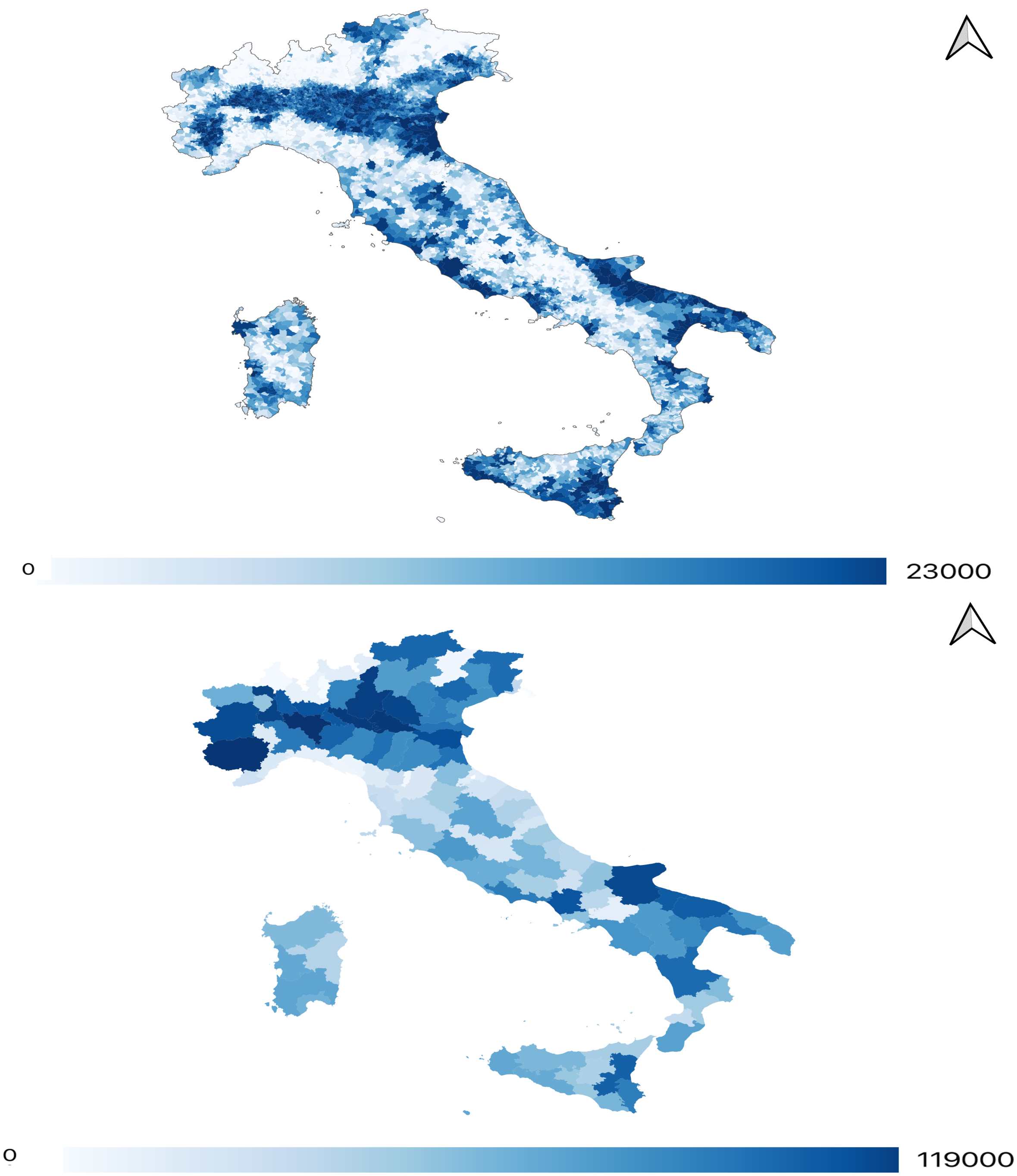

Figure 31: All the Irrigated Area in Italy by ISTAT in province and commune level

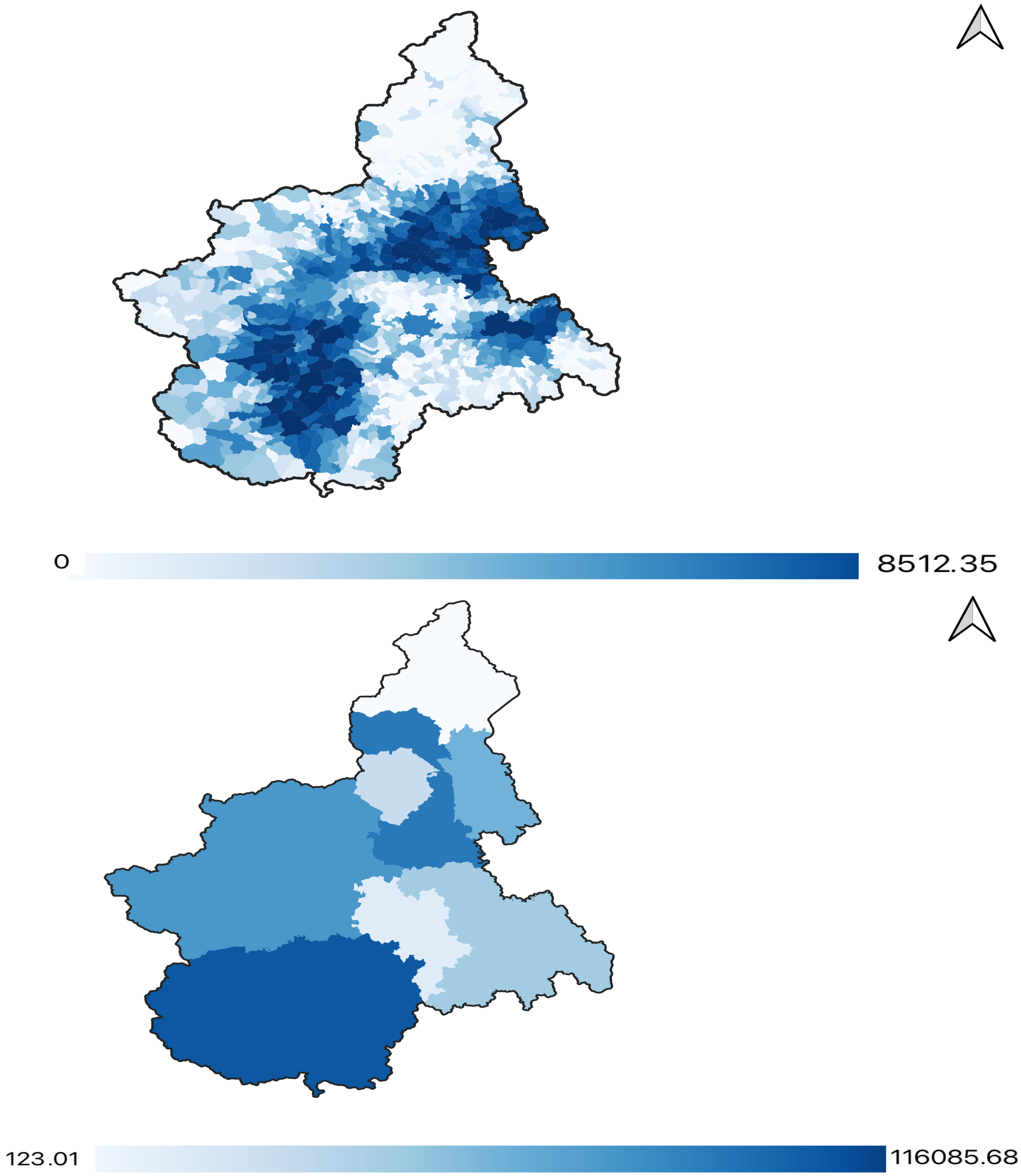

Figure 32: All the Irrigated Area in Piemonte by ISTAT in province and commune level

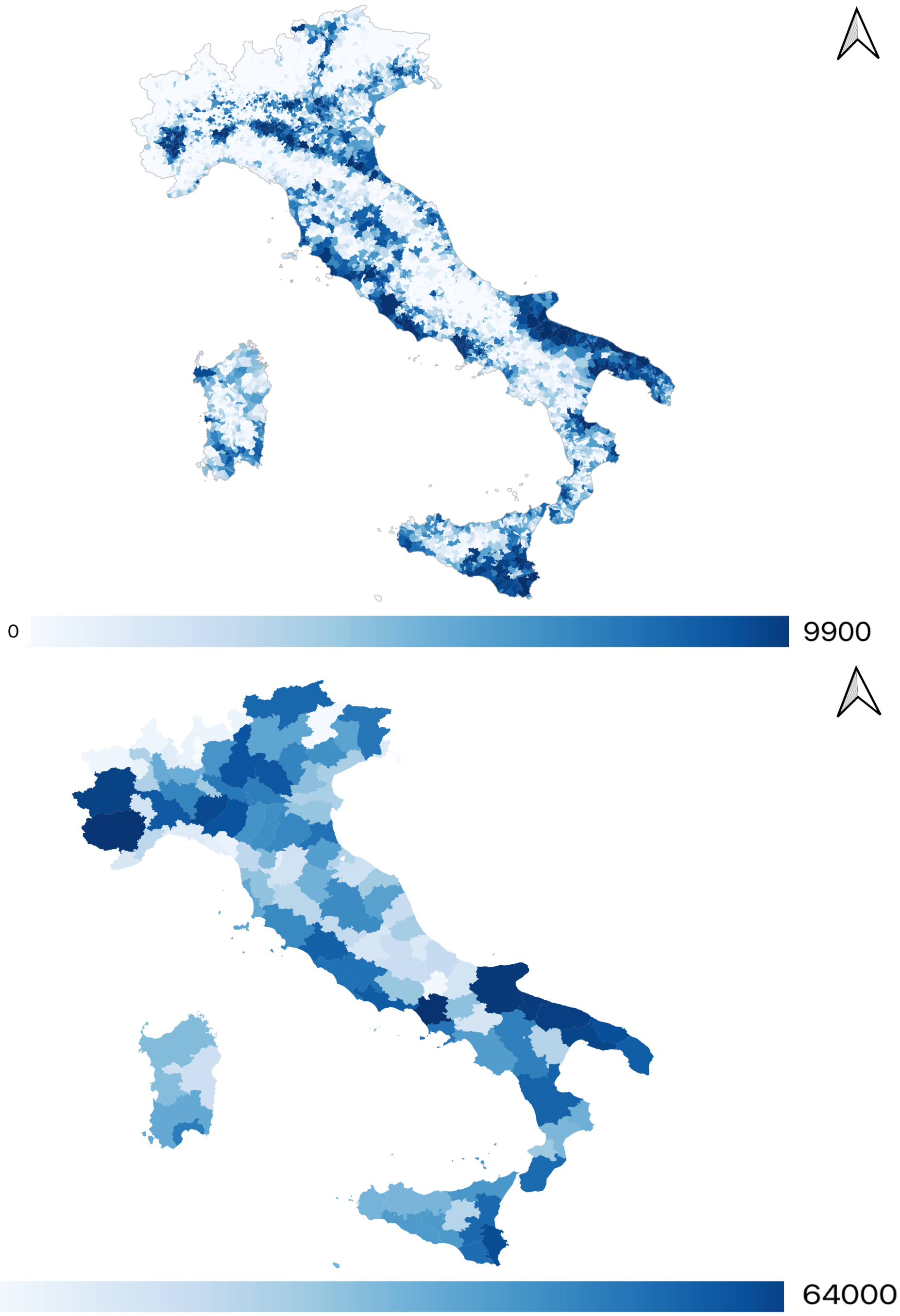

Figure 33: Area Irrigated by groundwater in Italy by ISTAT in province and commune level

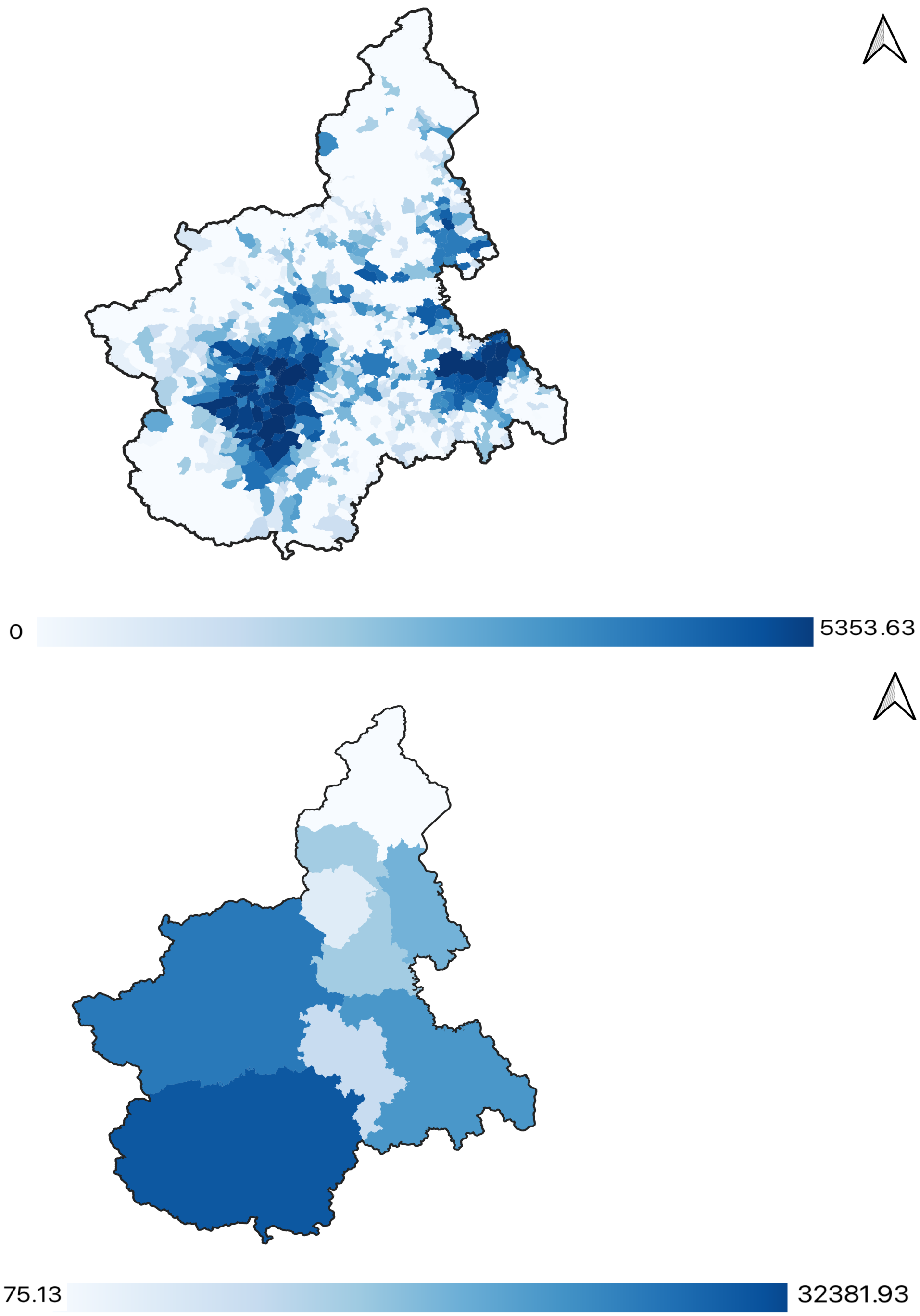

Figure 34: Area Irrigated by groundwater in Piemonte by ISTAT in province and commune level

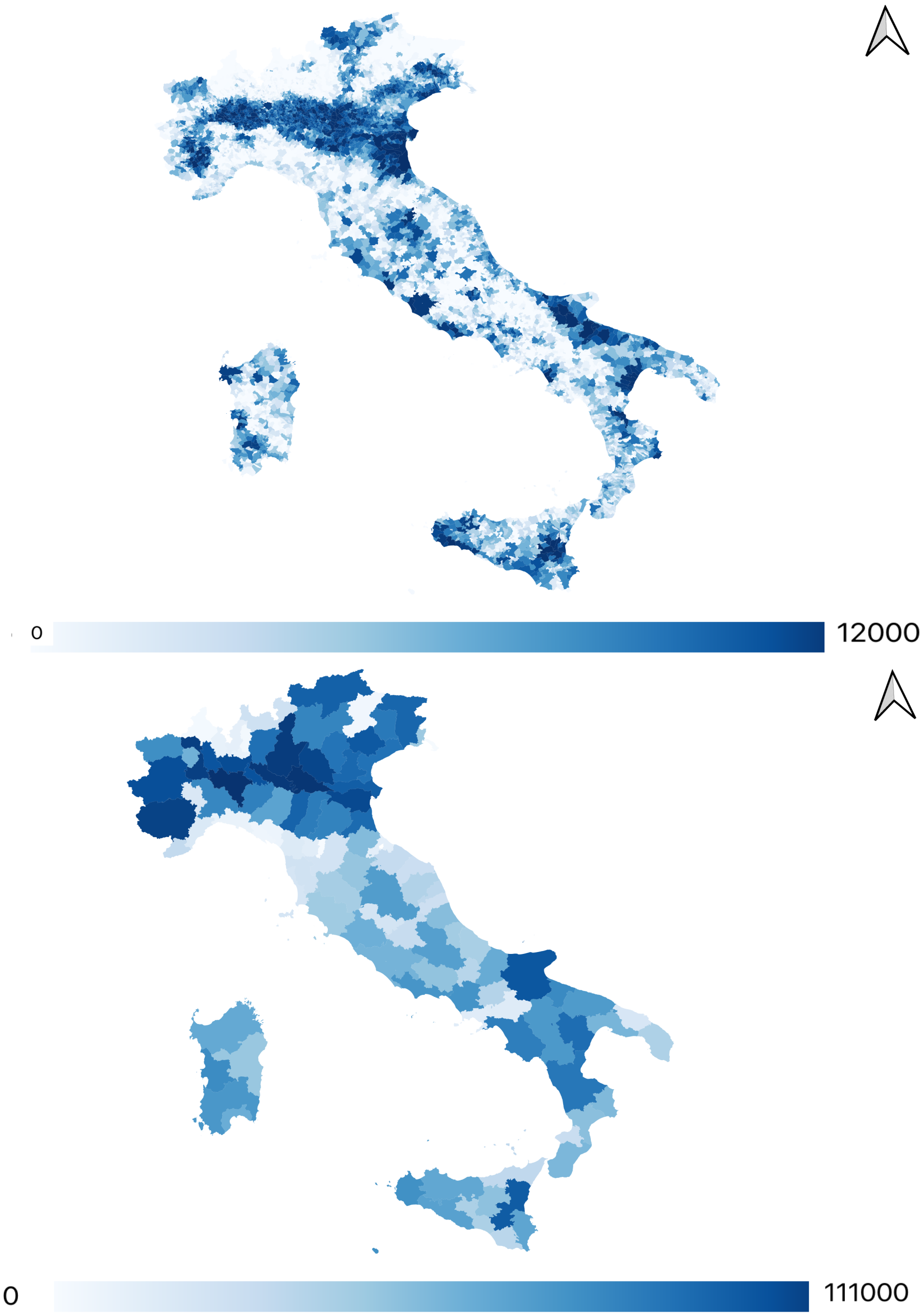

Figure 35: Area Irrigated by surface water in Italy by ISTAT in province and commune level

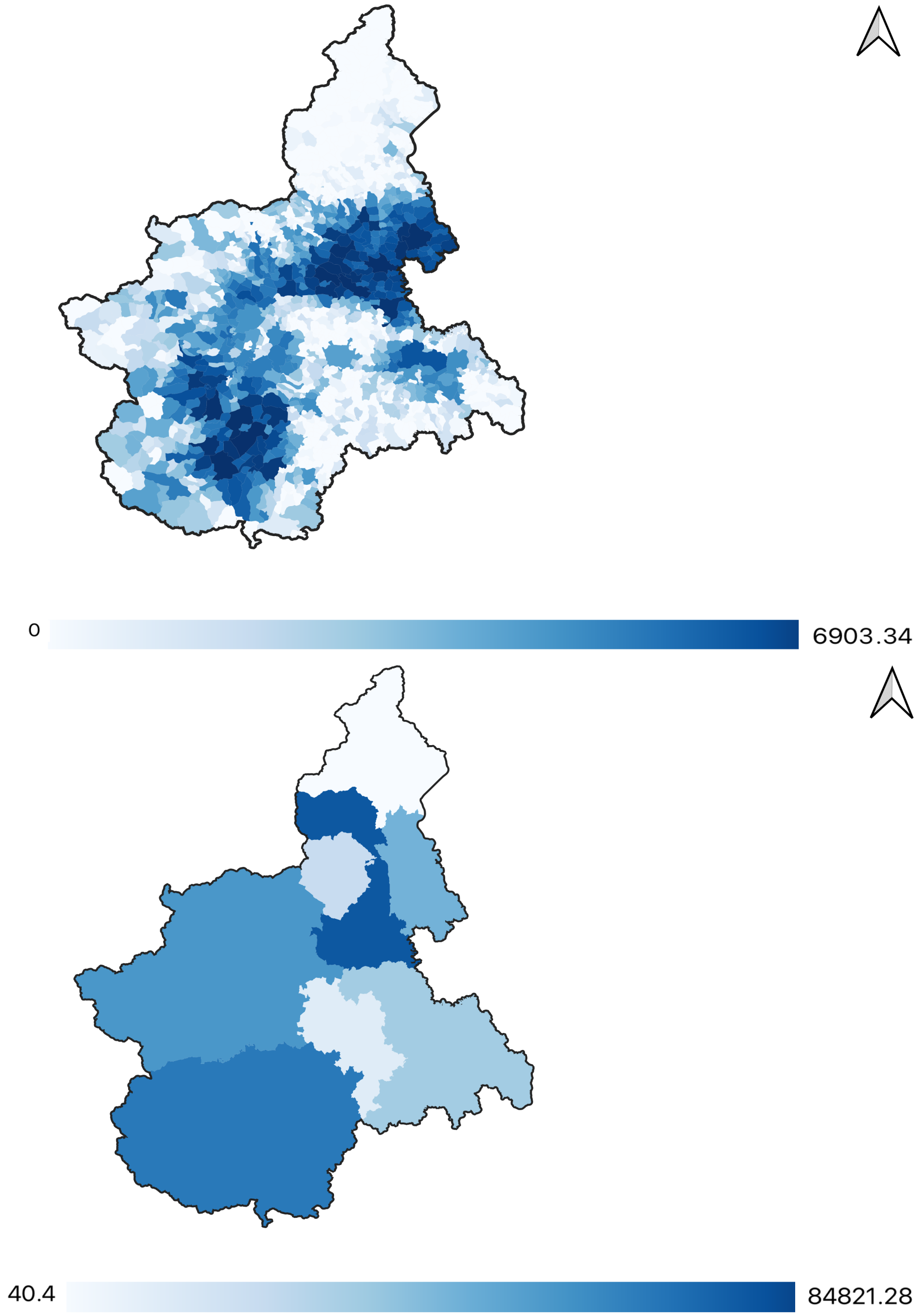

Figure 36: Area Irrigated by surface water in Piemonte by ISTAT in province and commune level

Appendix III - Representation of ISTAT Spatial Data for Irrigation Systems

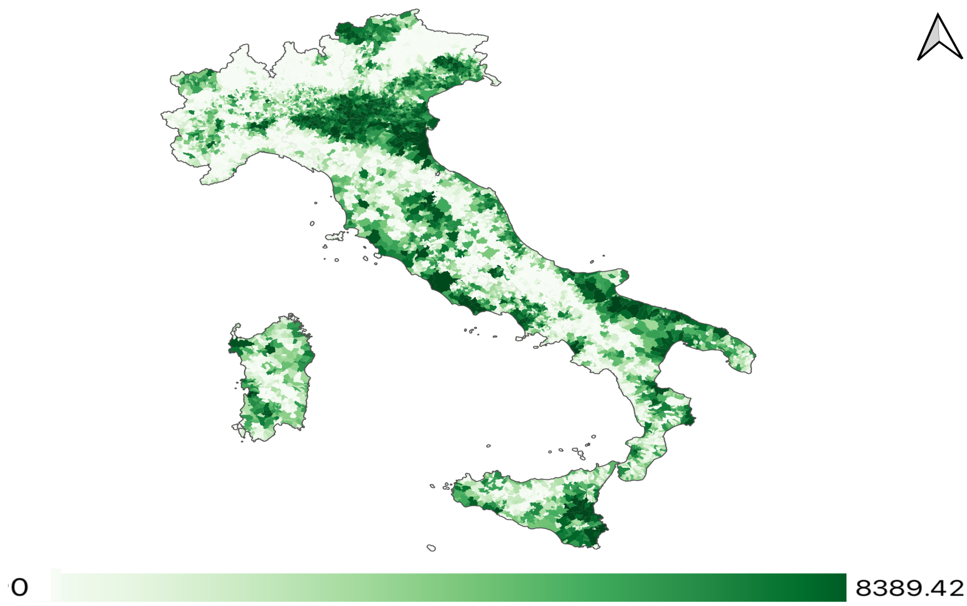

Figure 37: Area Irrigated with Aspersion(raindrop) in Italy

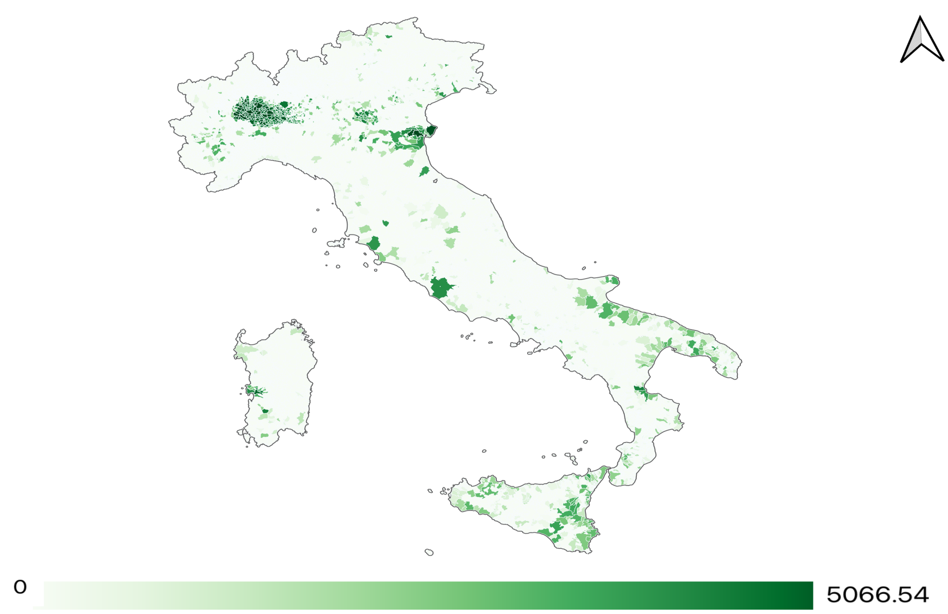

Figure 38: Area Irrigated with Flooding in Italy

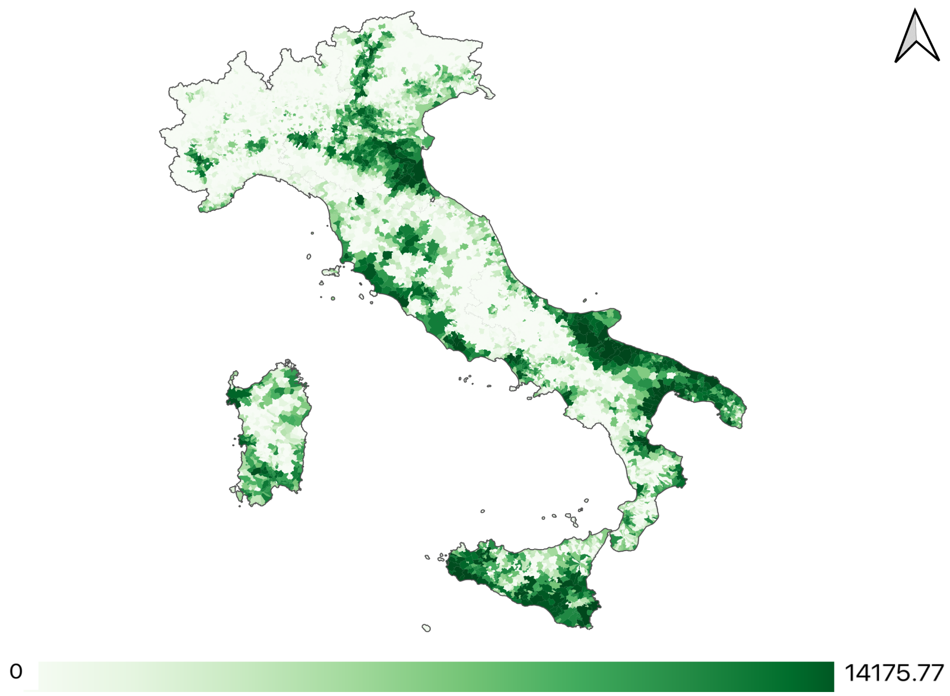

Figure 39: Area Irrigated with MicroIrrigation in Italy

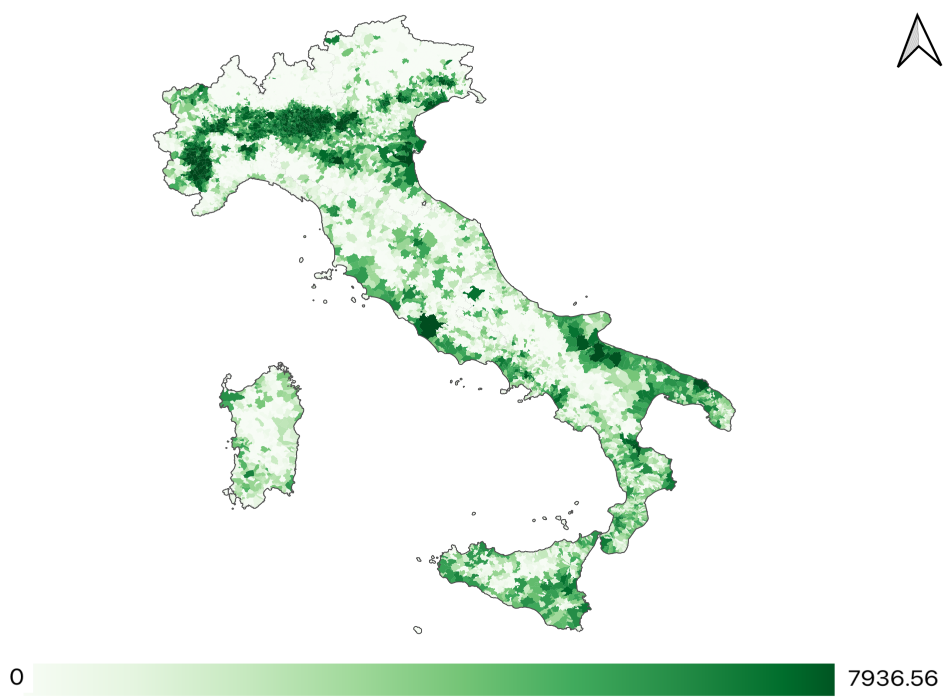

Figure 40: Area Irrigated with surface sliding and slide infiltration in Italy

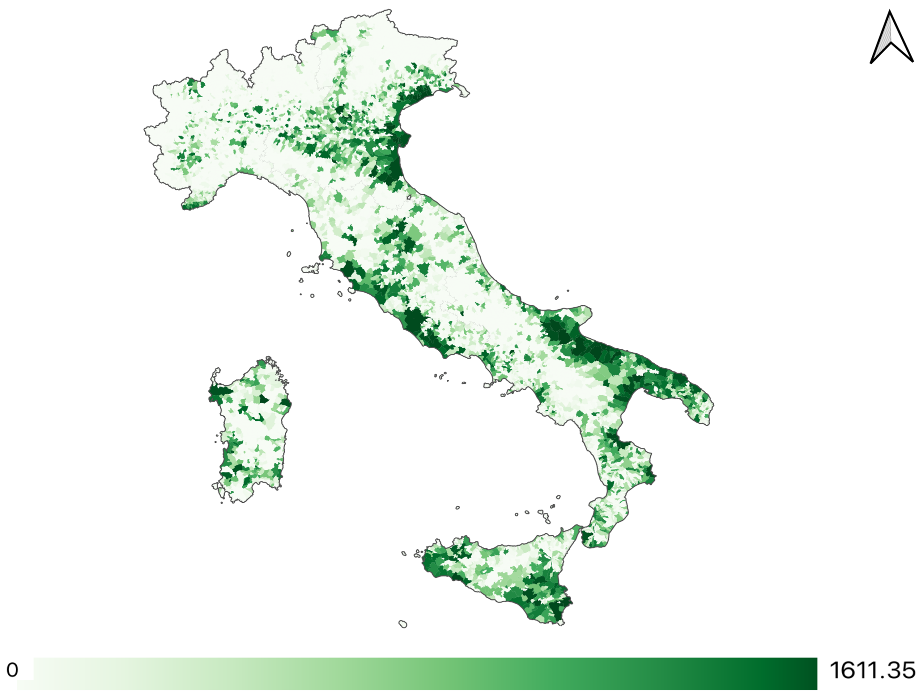

Figure 41: Area Irrigated with Other Irrigation Systems in Italy

Appendix IV - Hierarchical Bubble Presentation of Irrigation Systems in Italy

Figure 42: Bubble presentation of Area Irrigated with Aspersion(raindrop) in Italy

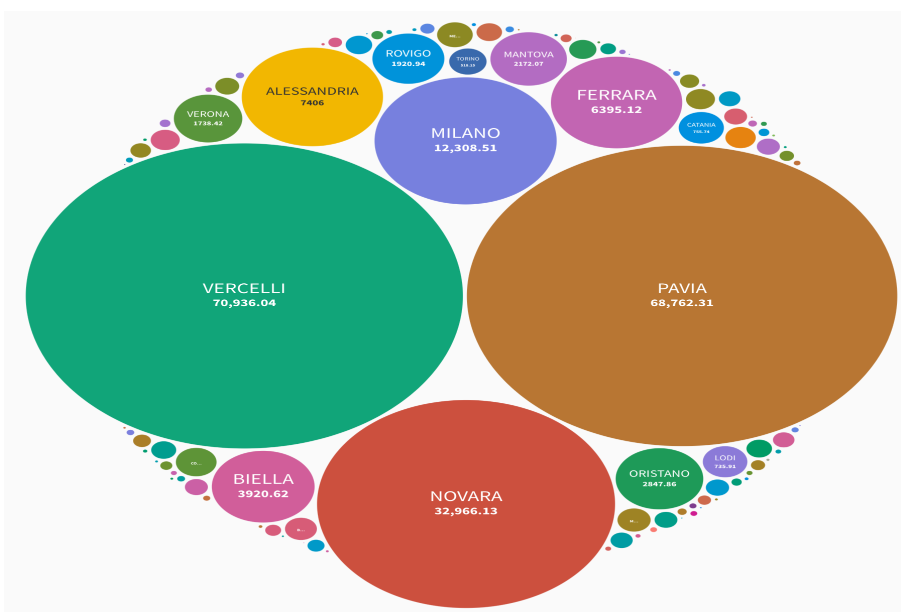

Figure 43: Bubble presentation of Area Irrigated with Flooding in Italy

Figure 44: Bubble presentation of Area Irrigated with MicroIrrigation in Italy

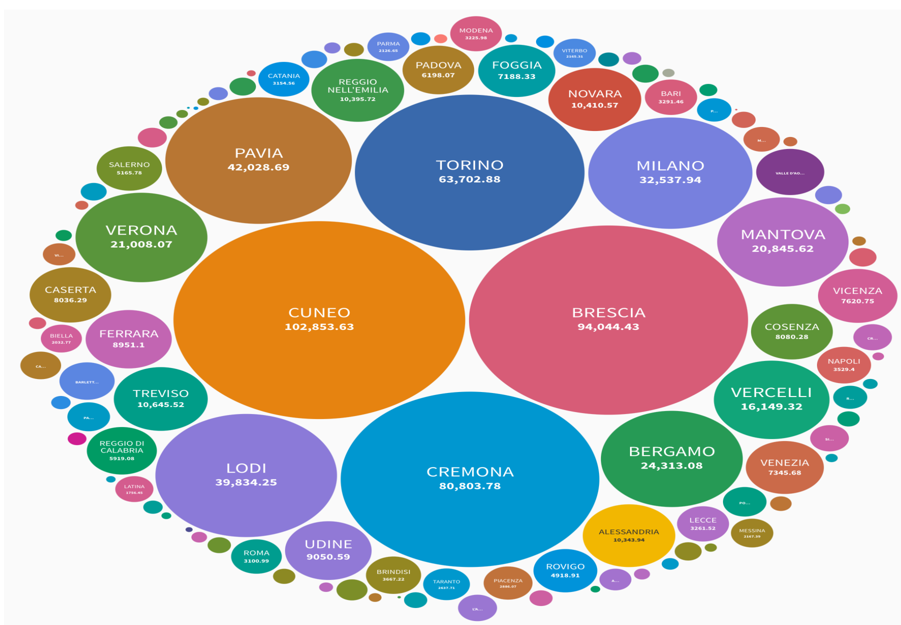

Figure 45: Bubble presentation of Area Irrigated with Surface Sliding and Slide Infiltration in Italy

Figure 46: Bubble presentation of Area Irrigated with Other Irrigation Systems in Italy

Appendix V - Representation of Comparison of Water Requirements and Irrigation Requirements in 2005-2014

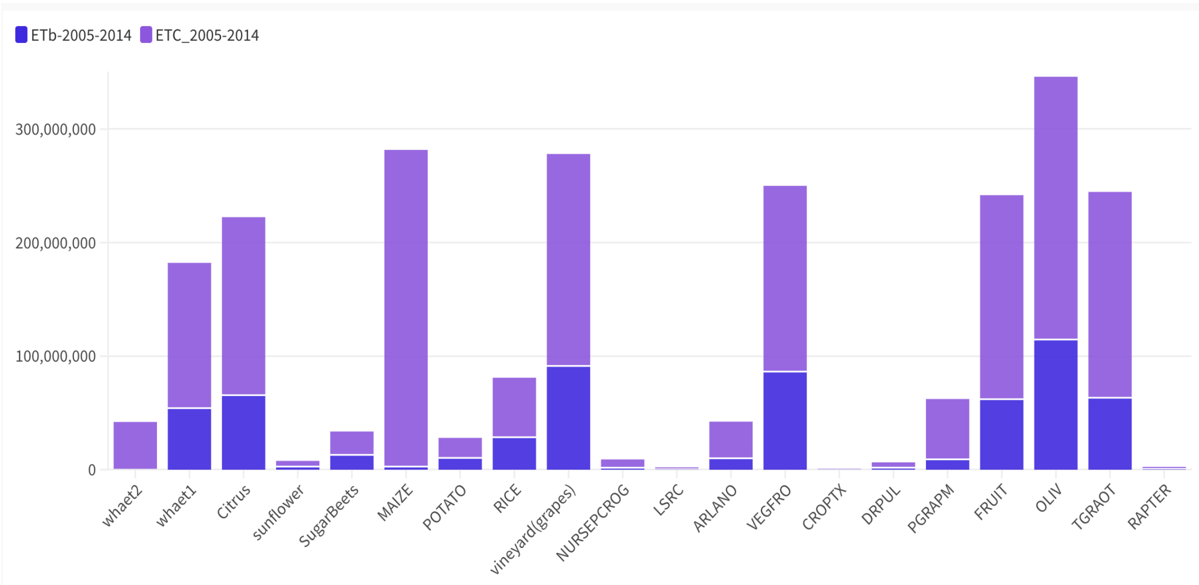

Figure 47: Comparison of Water Requirements and Irrigation Requirements in Italy in 2005-2014

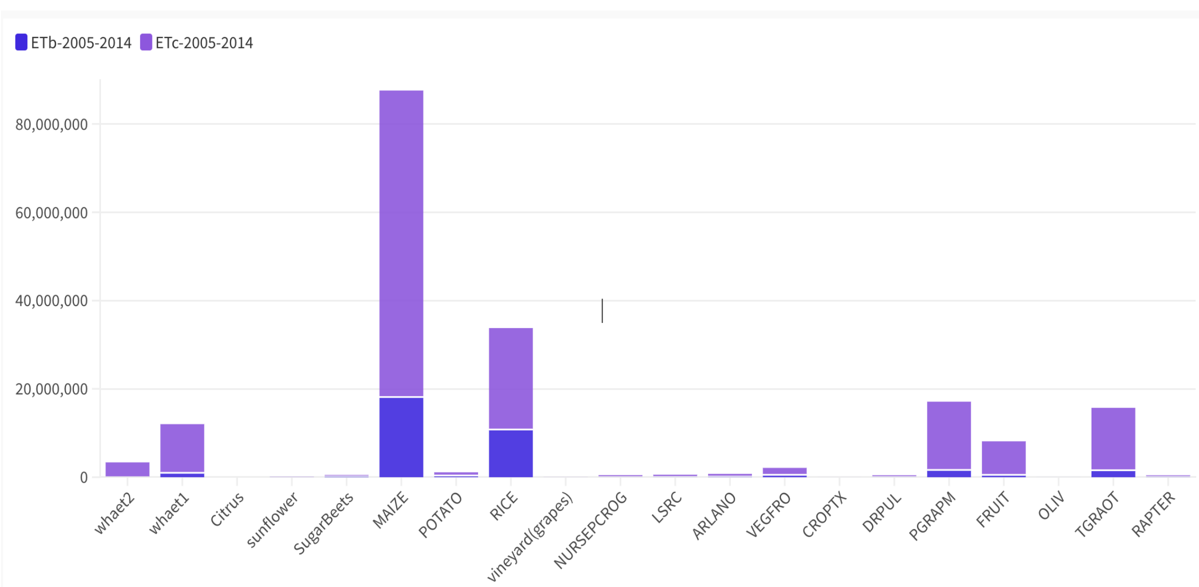

Figure 48: Comparison of Water Requirements and Irrigation Requirements in Piemnote in 2005-2014

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