INOPIA model for drought forecast and its consequences on water resources – example of the City of Foligno in Italy

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INOPIA MODEL FOR DROUGHT FORECAST AND ITS CONSEQUENCES ON WATER RESOURCES -EXAMPLE OF THE CITY OF FOLIGNO IN ITALY

Master's Thesis

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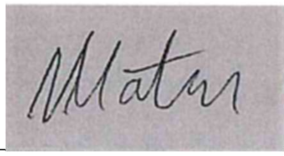

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INOPIA MODEL ZA PROGNOZU SUŠA I POSLJEDICA NA VODNE RESURSE- PRIMJER GRADA FOLIGNA U ITALIJI

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Rad izrađen: Sveučilište u Zagrebu
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Sažetak

Na zaštitu okoliša i upravljanje vodama utječu nestašica vode i suša. Neodrživo upravljanje vodama može negativno utjecati na prirodu i društvo. To uključuje onečišćenje, prekomjernu potrošnju i predviđene učinke klimatskih promjena u sušama. Vodeni ekosustav mogao bi biti izložen većem riziku ako se vodnim resursima ne upravlja pravilno. U ovom diplomskom radu prikazana je definicija suše i utjecaj suše, te pravni temelj upravljanja sušom u EU. U sklopu ovog diplomskog rada predstavljen je alat INOPIA koji se koristi za najavu vodnih kriza i procjenu mjere hitne vodoopskrbe. Također, alat za podršku implementiran je na primjeru grada Foligno, Italija i njegove okolice.

Ključne riječi: INOPIA, upravljanje sušom, Foligno, nestašia vode, upravljanje vodom, alat za podršku

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Master's Thesis

INOPIA MODEL FOR DROUGHT FORECAST AND ITS CONSEQUENCES ON WATER RESOURCES - EXAMPLE OF THE CITY OF FOLIGNO IN ITALY

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Abstract

Environmental protection and water management are affected by water scarcity and drought. Nature and society may be adversely affected by unsustainable water management. This includes pollution, overconsumption, and, predicted climate change effects in droughts. The aquatic ecosystem could be at greater risk if water resources aren't managed properly. In this Master’s Thesis definition of drought and impact of drought are presented, also the legal basis of drought management in EU. As part of this Master’s Thesis, the tool INOPIA used to announce water crises and assess the measure for emergency water supply is presented. Also, the support tool is implemented on example of City of Foligno, Italy and its surrounding.

Keywords: INOPIA, drought management, Foligno, water scarcity, water management, support tool

Thesis contains: 52 pages, 7 tables, 25 figures and 36 references.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Environmental protection and water management are affected by water scarcity and drought according to EDO - European Drought Observatory. Nature and society may be adversely affected by unsustainable water management. This includes pollution, overconsumption and, predicted climate change effects in droughts. If water resources aren't managed properly, the aquatic ecosystem could be put at greater risk. As a result of inadequate water use planning, rivers and groundwater are heavily exploited in times of drought and water scarcity, which threatens the survival of related fauna and flora as well as endangers drinking water resources.

Water scarcity can be defined as: "a situation where there are insufficient water resources available to satisfy long-term average water demand" according to the guidelines of the European Expert Network on Water Scarcity and Droughts called *Guidelines for preparation of the Drought Management Plans* (Global Water Partnership[GWE], 2015) and *Drought Management Plan Report* from November 2007 (European Commission, 2008). Water scarcity occurs when the availability of water is lower than the demand for water for a prolonged period. There are two possible causes of water scarcity: drought conditions and man-made sources. Long lasting (few months to few years) decrease in precipitation creates drought conditions. Natural forces and human actions are thus both responsible for generating water scarcity. Both factors exert impacts on water supply systems, resulting in a temporary imbalance between supply and demand. From a climatological perspective, drought is quantified with frequency, duration, severity, and the extent of precipitation anomalies (Romano et al., 2018; Hao et al., 2015). According to Romano et al. 2018 there are many more drought division rather than already generally accepted, such as meteorological, agricultural, hydrological, and socio-economic droughts. They usually happen in sequential steps and for different lengths of time, overlapping in some cases (Chung et al., 2000). As a result of such complexity, it is difficult to find comprehensive solutions in terms of mitigation and adaptation. A critical aspect of evaluating drought mitigation measures, is to establish an appropriate link between potential management actions and a drought state, as outlined in the *Drought Management Plan Report* (European Commission, 2008).

As part of this master's thesis, the tool used to announce water crises and assess the measure for emergency water supply is presented. The aim of the thesis is to describe INOPIA support tool for announcing water shortage in water supply system. Also, the support tool is implemented on example of City of Foligno, Italy and its surrounding.

In the second chapter definition and impact of drought are presented. In the third chapter legal basis of drought management in Europe are presented. In the next chapter decision support tool INOPIA is described. In the fifth chapter, geological and hydrogeological characteristics as well as climatic variations of the Umbria region are presented. The sixth chapter presents the input data of the Foligno example. Also, output data for each segment of the water scheme built in INOPIA. In the seventh chapter, the most important results, which are characteristic of the selected example, are presented.

2. DEFINITION OF DROUGHT AND IMPACT OF DROUGHT

2.1. Definition and concepts related to drought

Significant decrease in precipitation, usually lasting from few months to few year, creates a natural event called drought. According to *Drought Management Plan Report* (European Commission, 2008), drought events have regularly occurred in the past thirty years and their duration and affected areas differed greatly. Droughts can't be controlled but resulting impacts can be mitigated, primarily with adequate management. It has been shown that drought can trigger a so called "water scarcity". Water scarcity is defined by long-term imbalance in water availability and water demand in a certain area. However, in comparison to drought, water scarcity can be also caused by man-made actions. These phenomena, drought and water scarcity, are considered to be the water shortage conditions.

There are a number of factors that might contribute to drought from a climatological point of view, including its frequency, duration, severity, and the extent of any anomalies in precipitation (Romano et al., 2018). It is generally accepted that droughts are categorized as meteorological, agricultural, hydrological, and socio-economic. Recognizing the factors that contribute to the causal chain from meteorological to socio-economic droughts is rather complex because of the complexity of drought phenomena. Due to the seriousness of this natural phenomenon, it is very difficult to find a universal solution for drought mitigation as shown in the *Drought Management Plan Report* (European Commission, 2008). The first step is to find a link between drought starting points and possible management measures.

2.2. Impact of drought

As a result of droughts, large areas and populations are affected, and this has wide-ranging effects on society, the economy, the environment, and therefore the sustainability of the development process. In economic terms, the impacts of drought can be classified into primary and secondary (Gil et al., 2013). The primary impact directly affects water scarcity, the environment, society and/or economy of a given area. Examples of the primary impact of drought include: crop loss, limited public water supplies, reduced energy production and drying up a wetland. Secondary impacts are no longer a direct result of water scarcity but are impacts at a distance from the drought-affected area. The indirect effects of drought influence regions far from where the drought originated and drought effects persist long after the drought has ended. They affect biodiversity and ecosystems, food prices, human health, and poverty. According to Vogt et al., 2018 the sectors most affected by droughts are:

- Environment – Animals and plants has to have an access to water; drought conditions can affect their food supply and damage their habitats. It is possible that the damage is only temporary. Meaning, their food supply and habitat will get back to normal once the drought is finished. However, it is also possible for drought to result in permanent degradation of land and ecosystems or desertification in some cases.
- Agriculture - droughts can harm crops and cause other losses to agriculture. A farmer may spend more money if irrigation costs increase, new wells need to be drilled, or animals need to be fed and given water. Consequently, agriculture-related industries, such as tractor manufacturers and food producers, may suffer.
- Power generation (hydro, thermal and nuclear) - water stored in upstream reservoirs or river flows determine hydroelectricity production. In a drought, production levels may be lower. In order to satisfy peak electricity demands, alternative means will be needed (e.g., gas turbines). Losses from hydroelectricity infrastructure are affected by drought severity and hydroelectricity infrastructure. Moreover, during droughts, reduced cooling water availability can lead to power generation reductions and even power plant shutdowns.
- Buildings and infrastructure - in response to changes in moisture, soils swell and shrink. When soil shrinkage is pronounced under drought conditions, serious damage can occur to buildings and infrastructure.
- Commercial shipping - During low-flow conditions, businesses that rely on water transportation to receive and deliver goods and materials may find it difficult to navigate the streams, rivers, and canals in a safe and efficient manner. As a result, fuel and food prices may increase.
- Social impacts - As a result of droughts, people can experience safety and health issues, poverty traps, conflicts between them, and lifestyle changes.

3. LEGAL BASIS OF DROUGHT MANAGEMENT IN EUROPE

3.1. Policy framework

Council and European Parliament adopted *Directive 2000/60/EC* (2000) on 23rd of October 2000 to establish a framework for EU action in the field of water policy: *Water Framework Directive 2000/60/EC* (WFD). WFD provides a framework for protecting and enhancing surface waters (lakes, rivers, coastal waters and transitional waters), and groundwater. According to the WFD, the most important legislative instrument for protection of water across the EU, Member States must implement new EU water policies based on unified water management principles. Water management at the basin level is an important concept of the WFD. In order to achieve "good water status" in surface water bodies, each river basin district must develop River Basin Management Plans (RBMPs) (European Environment Agency). In addition to being developed at the national level, RBMPs must also be developed at the basin level. Three levels of cooperation are expected for the WFD to succeed: The European Community, river basins, and national levels. In drought strategy the interaction between EU level, river basin level and national level are shown in Figure 3-1.

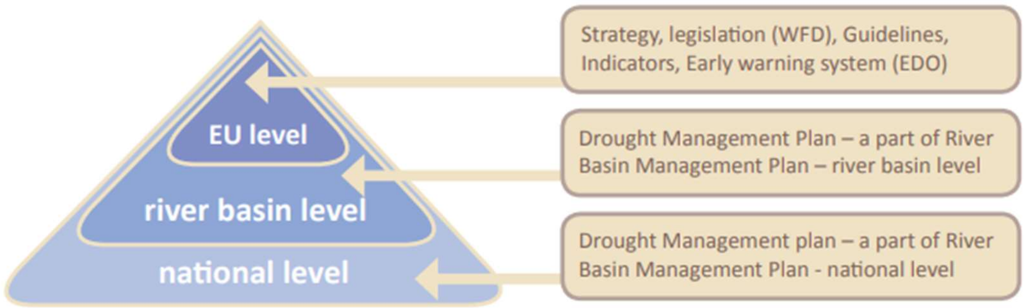


Figure 3-1. The interaction between EU level, river basin level and national level in Drought strategy (GWP CEE: Guidelines for preparation of the Drought Management Plans, 2015)

With the aim of establishing a common approach to implement the WFD in Member States, the Common Strategy for Implementation of the WFD (CIS) was founded in 2001 at the community level. Water Directors (Member State representatives) have developed and approved several technical guidance documents as part of the CIS process. These documents are not legally binding; they have become almost binding due to the consensus among all EU countries. Although, many actions have been taken at the EU level to develop drought policy, the preparation of RBMPs is the primary goal of CIS. Another CIS task was to develop technical documents and policy, on the Community level. These are the foundation of EU drought policies and are listed below:

- *Drought Management Plan Report Including Agricultural, Drought Indicators and Climate Change* (Report 2007) – guidelines for producing a Drought Management Plan to meet basic RBMPs principles.
- *Communication from the Commission to the European Parliament and the Council - Addressing the challenge of water scarcity and droughts in the European Union* (COM (July 2007) –policies and actions addressing water scarcity and drought problems (hereinafter Communication 2007).
- *A Blueprint to Safeguard Europe's Water Resources* (November 2012) – defining and addressing obstacles to protect water resources is the purpose of this policy document. Drought-related vulnerabilities and solutions are discussed in this document (hereinafter Blueprint).

This revision of the policy instruments follows the publication of the *Guidelines for preparation of the Drought Management Plans* (GWE, 2015)*, Development and implementation in the context of the EU Water Framework Directive* (GWE and Central and Easter Europe [CEE], 2015), which defined a seven-step process in order to develop a plan in the context of the EU *Water Framework Directive 2000/60/E*. Its goal is to identify other EU policies that are relevant to the management of droughts in multiple fields and to propose alternatives based on *Integrated Drought Management Programme* (IDMP) from 2020 (World Meteorological Organization, 2020).

Currently, at EU level, there are no clear directives and policies dedicated exclusively to drought management. However, there are existing legislation and policies related to drought management within policies related to water, agriculture, climate change, energy, industry, biodiversity, transport, protection of nature which could to a certain degree provide legal frame for drought management.

In the *Water Framework Directive 2000/60/EC* (2000), a few provisions deal with quantitative aspects related to the issue of water scarcity, which are addressed multiple times throughout the directive. A joint *Integrated Drought Management Programme* (World Meteorological Organization, 2020) of the World Meteorological Organization (WMO) and the *GWE CEE* addressed this issue and developed guidelines for the development of a *Drought Management Plan* (European Commission, 2008) as part of the RBMP. In order to reach environmental goals, drought management plans and river basin management plans can work together. Several provisions of the Water Framework Directive deal with quantitative problems that are related to water scarcity. WMO and the Global Water Partnership Central and Eastern Europe (GWP CEE) jointly developed an *Integrated Drought Management Programme* (WMO, 2020) in response to this issue and introduced suggestions for drought management plans within the regional drought management plans. There is potential for an improvement in the overall execution of the *Water Framework Directive 2000/60/EC* (2000) by establishing a solid link with EU water policy. This connection provides the frame for the development of a national drought policy that is based on risk reduction principles. Table 2.1 shows the strategies / policies as well as the corresponding existing implementation instruments related to drought and water scarcity mitigation based "*The revision of the policy instruments and their potential to contribute to EU droughts and water scarcity*" policies from 2020 (GWP CEE, 2020).

Table 3-1. The revision of the EU policy instruments related to drought and water scarcity mitigation (Modified according to The evaluation chart from Revision of the policy instrument and their potential to contribute to EU droughts and water scarcity policies)

Strategy/policy	Existing implementation instrument	Criteria for justification how selected policy/document support drought management Not mentioned(-);generally addressed(0);support actions(+)				
		Monitoring & data collection	Incentives to water efficiency & circular economy	Knowledge production and research on drought preparedness and resilience	Operational measures to improve drought management(and to develop DMP)	Financial instruments to adapt/mitigate droughts
Water						
Water Framework Directive 2000/60/EC	River Basin Management Plans	+	0	0	+	0
Floods Directive 2007/60/EC	Flood Risks Management Plans	0	-	0	0	-

Water Communication on water scarcity and droughts COM (2007) 414, supplemented by a 2012 review of the European WS&D Policy(COM(2012)672)	Drought Risk Management Plan	+	+	+	+	0
Groundwater directive 2006/118/EC	River Basin Management Plans	0	-	-	0	-

3.2. Drought management plan report

In several countries and based on a review of their drought management policies, it is apparent that they have encountered drought episodes. Instead of developing comprehensive, long-term drought preparedness policies and action plans, which could greatly reduce the risk and vulnerability of extreme weather events, they tend to use a crisis-management, which de facto establishes an emergency program to alleviate the drought effects. (Food and Agriculture Organization of the United Nations, 2021). In recent years, according to, *Drought Management Plan Report* (European Commission, 2008) from November 2007 by Water Scarcity and Droughts Expert Network. There has been observed a shift from crisis towards the risk management approach in dealing with droughts. *Drought Management Plan Report* (including agricultural, drought indicators and climate change aspects) includes general guidelines to develop a Drought Management Plan (DMP), complying with WFD environmental objectives. The main items summarized in the report that are necessary to develop a DMP are:

- The quantitative indicators that determine when an exceptional circumstance occurs and ends as well as a quantitative scale for the severity level it reaches;
- During each drought phase, measures should be taken to prevent deterioration of water status and soften negative effects of drought;
- Plan for drought management and subsequent revisions to the existing plan.

An effective drought plan will enable to plan for and to respond effectively to droughts. It will also help to address challenges the plan implementation, including often reviews of the accomplishments and priorities. Great climatic and geographic variability influences drought complexity. This is why it seems to be inevitably to develop different indicators to calibrate and compare local or national indicators based on the information available when there is enough data available (Drought Management Plan Report, Water Scarcity and Droughts Expert Network, 2007).

3.3. Content and basic elements of drought management plans

Three primary elements should be supported by a drought management protocol to aims of *Drought Management Plan Report* (European Commission, 2008): 1) droughts early warning services, 2) indicators and thresholds for each stage of drought as they intensify and diminish, and 3) steps to be taken to reach specific objectives during each drought phase. These three goals are needed in order to ensure that DMP is transparently developed. According to *Drought Management Plan Report, Water Scarcity and Droughts Expert Network, 2007* the documents integrating the DMP should encompass:

- A description of the basin's general characteristics in drought conditions;
- The basin's past experiences of drought;
- Droughts characteristics within the basin;
- Implementation of a drought warning system;
- A list of precise and concrete measures for droughts prevention and mitigation;
- Organizational structure of the DMP (committee, board or working group);
- Update and maintenance of the DMP;
- Plans for public supply;
- Prolonged drought management.

3.4. Overview and examples of existing indicators to identify and manage drought

Monitoring of droughts is extremely important because they are part of the global climate system. Each year, droughts are one of the costliest natural hazards; they have widespread and significant impacts that can affecting many economic sectors. As the drought develops one can observe changes in, temperature, precipitation, surface water, and groundwater supplies. Droughts can be classified according to their strength, location, and time of duration. Depending on the season and the region, drought indicators are often used to track droughts. *In the Handbook of Drought Indicators and Indices* (WMO and GWP, 2016), the indicators and indices are discussed and provide an option for identifying the droughts based on the strength, location, and time of duration. *Handbook of Drought Indicators and Indices* is part of *Integrated Drought Management Tools and Guidelines Series* (WMO and GWP, 2014). It was written by Mark Svodoba and Brian Fuchs of the National Drought Mitigation Centre at the University of Nebraska-Lincoln.

As part of drought monitoring, a series of drought indicators (e.g., precipitation, soil moisture, reservoir levels, river flows, groundwater levels) are analyzed, which represent different parts of the hydrological cycle or specific impacts associated with droughts (e.g., vegetation water stress) (WMO and GWP, 2016). Variety of indicators/indices is necessary to monitor different parts of the hydrological cycle. There are several commonly used drought indicators/indices covered in this handbook. Indicators and indices are used in areas that are prone to droughts to advance monitoring, early warning, and information delivery systems in the frame of risk-based drought management (WMO and GWP, 2016).

The indicators presented in the *Handbook of Drought Indicators and Indices* are grouped as follows: meteorology, hydrology, soil moisture, composite, remote sensing and modelled. Also, the indicators are grouped by type and ease of use. A ‘traffic light’ approach is used for each indicator in the ease-of-use classification: green, yellow, or red light. According to user needs, data availability, knowledge, and computer resources available for implementation, one, more, or none at all indicators may be used.

One or more of the below listed criteria must be acquired for indicators and indices to be considered green (WMO and GWP, 2016):

- A program to run the index is publically and readily available and;
- Daily data are not necessary;
- Index output is already produced operationally and is publicly online.

One or more of the below listed criteria must be acquired for indicators and indices to be considered yellow (WMO and GWP, 2016):

- Multiple inputs are required for calculations;
- A program to run the index is not available publicly;
- A single input may be required, but there is no code is available;
- Minimal complexity of the calculations is provided.

One or more of the bellowed listed criteria must be acquired for indicators and indices to be considered red (WMO and GWP, 2016):

- A program has yet to be written to calculate the index based on literature
- The output products are not readily available;
- The index is obscure, not widely used, but could be of use;
- The index is consisted of modeled input or is a part of the complex calculations.

3.4.1. Examples of existing drought indicators and indices

In this subchapter, existing drought indicators and indices from different categories that are widely used will be presented in the Table 3-2.

Table 3-2. Examples of existing drought indicators and indices

Name	Category	Ease of use	Origins
Standardized Precipitation Index (SPI)	Meteorology	Green	Research and work done in 1992 by McKee at Colorado State University, United States. In January 1993, They presented the results of their work at the 8th Conference on Applied Climatology. The WMO recommended using SPI as the main meteorological drought index in 2009 (Hayes, 2011).
Palmer Hydrological Drought Index (PHDI)	Hydrology	Yellow	Palmer developed this index with the U.S. Weather Bureau in the 1960s.
Standardized Reservoir Supply Index (SRSI)	Hydrology	Yellow	Gusyev et al. (2015) developed in Japan

- Standardized Precipitation Index (SPI)

  Characteristics: Calculates precipitation probabilities using historical precipitation data at any location over any number of timescales (from 1 to 48 months). Like other climate indicators, time data are not required to be of a certain length to be used for SPI calculations. Ideally, a time series should cover at least 30-year period.

For whatever timescale, a drought event is considered when SPI achieves continuously negative value. McKee et al. (1993) stated that drought event should be considered when SPI is less than -1. However, no common standard has been reached in the meantime. Some researchers use a threshold that is less than 0 (but not quite -1), while others use a threshold that is less than 1 (WMO and GWP, 2016) In the Table 3-3. classification of SPI according to Makakiva et al. (2016) is presented.

Table 3-3. SPI classification (Makakiya et al., 2016)

SPI	Classification
2.00>	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
0 to 0.99	Near Normal
0 to -0.99	Mild drought
-1 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought

Input parameters: Precipitation, mostly monthly datasets, but the flexibility of computer programs allows using daily or weekly values.

- Palmer Hydrological Drought Index (PHDI)

Characteristics: The basis of this index is the original Palmer Drought Severity Index (PDSI), but it is modified in order to account for long-term dryness that influences streamflow, water stock, and groundwater. PHDI could be used to calculate drought end time by comparing the current value of moisture received with moisture needed to end it. There are four drought categories: near normal, occurring approximately 28%–50% of the time: mild to moderate, occurring approximately 11%–27% of the time; severe, occurring approximately 5%–10% of the time; and extreme, occurring approximately 4% of the time (WMO and GWP, 2016)

Input parameters: Precipitation and monthly temperature (Palmer, 1965)

- Standardized Reservoir Supply Index (SRSI)

Characteristics: Similarly, to the SPI index, the monthly averages are used to calculate a probability distribution function of reservoir storage data. It is used to give the information related to water supply for a region or basin in the range from −3 (extremely dry) to +3 (extremely wet) (WMO and GWP, 2016).

Input parameters: Average reservoir storage volumes and monthly reservoir inflows (Gusyev et al. 2015).

However, these kinds of tools do not adopt or partially adopt indicators to characterize drought, scarcity, and related impacts and the links among them, as required in the framework of the Drought Management Plan (Romano et al., 2018). Guided by this idea, CNR-IRSA started the development of INOPIA in 2019, which was conceived as a decision support tool for the early shortage indicators. More about INOPIA follows in the subsequent chapter.

4. DECISION SUPPORT TOOL INOPIA

INOPIA, informative decision support tool was developed within the cooperation agreement between the Italian Presidency of the Council of the Ministry - Department of Civil Protection and the Research Institute on Waters of the National Research Council Italy (IRSA-CNR), signed on the 9th January 2019. Development of INOPIA started in 2019 and is still in the development phase. It is being developed within the project "Accordo tra la Presidenza del Consiglio dei Ministri - Dipartimento Protezione CIvile e l'Istituto di Ricerca sulle Acque del Consiglio Nazionale delle Ricerche", 11.9.2020 – protocollo PRE/0049513 del 18/9/2020 (Eng. Agreement between the Prime Minister's Office - Civil Protection Department and Water Research Institute of the National Research Council of Italy of 11/9/2020 (registered PRE/0049513 of 18/9/2020). The research activities are linked to a previous Collaboration Agreement between Presidency of the Council of Ministers-Department of Civil Protection and the Research Institute on Waters of the National Research Council ('Operational Agreement of 19.12.2006 between DPC and IRSA - Rep. 618 ') and guarantee a progress in operational terms. This progress is incorporated in the Sendai Protocol (Sendai Framework for Disaster Risk Reduction 2015-2030) (United Nations Office for Disaster Risk Reduction, 2015) and regulations on the subject of Civil Protection (Law 100/2012 "Urgent provision for the reorganization of the Civil Protection and Legislative Decree 1/2018") (Civil Protection Department, Presidency of the Council of Ministers).

In this thesis, the latest version of INOPIA was used. The tool was developed with the aim to meet the following goal of the cited agreement: Development of IT operating systems for announcing water crises in multi-resource-multi-user water systems. INOPIA is developed in QGIS environment to satisfy the following instructions within Agreement between the Prime Minister's Office - Civil Protection Department and Water Research Institute of the National Research Council of Italy:

- Implementation of the topological scheme of any water system starting from six basic topological elements: surface inflows; superficial reservoirs; underground reservoirs; water utilities; connections; management nodes;
- Calculation of the mass balance on the monthly scale on the reservoirs present in the reference topological scheme;
- Management module that allows, through an algorithm developed ad hoc, the estimation of the state of the resources (potted volumes) and of the capacity to satisfy

the connected water demands according to different management options, established by the user;

- Shortage risk analysis (failure to satisfy demand) on reservoirs present in the topological reference scheme.

In the frame of IT operating systems development aimed at predicting water crises, not only hydro meteorological variables but also infrastructure characteristics and water demand are taken into consideration. The INOPIA tool, whose basic functions will be listed below, enables risk assessment. Risk of non-satisfaction of demand caused by conditions of reduction of water resources after permanent anomalies of precipitation (Romano et al., 2018).

4.1. INOPIA QGIS Software

The INOPIA tool was developed in an open-source QGIS environment that makes it usable and easily accessible without purchasing licenses. Among the various free GIS software available, QGIS was chosen as it is the most widespread and used (Graser, 2015). QGIS is free and has the advantage of being supported by a community that is constantly evolving, so it is updated frequently. For the purposes of this thesis, QGIS version 3.22 “Białowieża” was used but also as a version chosen to support the plugin. QGIS is adequate because it supports the Python programming language used to develop INOPIA. Figure 4-1. Shows the appearance of the QGIS interface with the INOPIA plug-in shown in red frame.

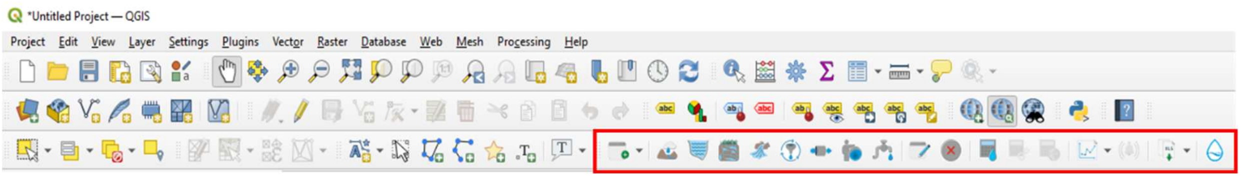


Figure 4-1. QGIS interface with INOPIA plug-in shown in red frame

4.2. General approach

INOPIA is applicable to water systems that exploit one or more resources (surface or groundwater) and distribute it to different types of users (drinking water, irrigation, industry…). Identifying water scarcity early signs is very important especially when droughts occur over a long time period. Water scarcity conditions are defined as the inability of a system to meet the user's demands. Meteorological impacts and climate change trends should be taken into account as well as the infrastructural and management characteristics of the system when considering the water supply system. Likewise, the analysis of the historical relationship between precipitation regimes, resources availability and reconstructed deficits allows calibration of early-warning decision support of possible water crises. Early warning is very important due to the early detection of water crises, after which timely action can be taken. INOPIA has its bases on the calculation of the monthly mass balance (water volumes) of a multi-resources-multi-users water system. Resources of water supply system can be natural or artificial. Natural resources are surface inflows, surface reservoirs, springs and underground reservoirs. Artificial resources can be surface reservoirs and alternative resources. More about each element will be presented in next chapter.

4.3. INOPIA toolbar

INOPIA represents a generic water supply system through topological elements. In INOPIA, the user creates a water supply scheme using eight topological elements. Five of the eight topological elements represent water resources (INFLOW, RESERVOIR, WELLS, SPRING, and ALTERNATIVE SOURCE). The USER element represents all potential users determined by the need for water that can change over time. The USER element is connected using the CONNECTOR element with one or more specific resources. The crucial element of INOPIA is the MANAGEMENT NODE. With which user of INOPIA sets priorities of water needs for USER element and distribution of resources to users.

In Figure 4-2. INOPIA toolbar is presented.

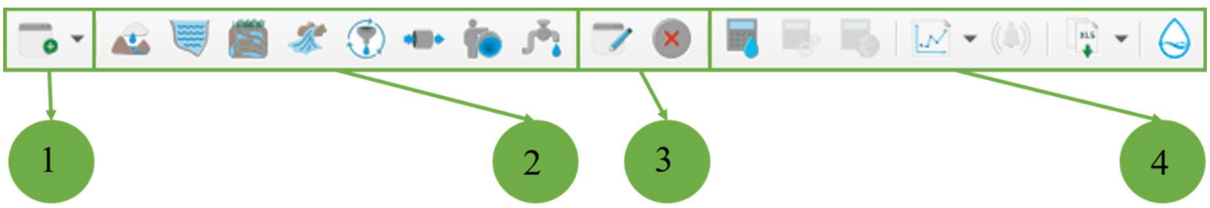


Figure 4-2. INOPIA toolbar

In the Section 1, the icon allows the user to create a new INOPIA project into QGIS project. Once clicking on the icon user needs to name a new project. Only one INOPIA project can be loaded at time.

The Section 2 shows the resources, user, connector, and management node elements of INOPIA and the elements are enlarged in Figure 4-3.

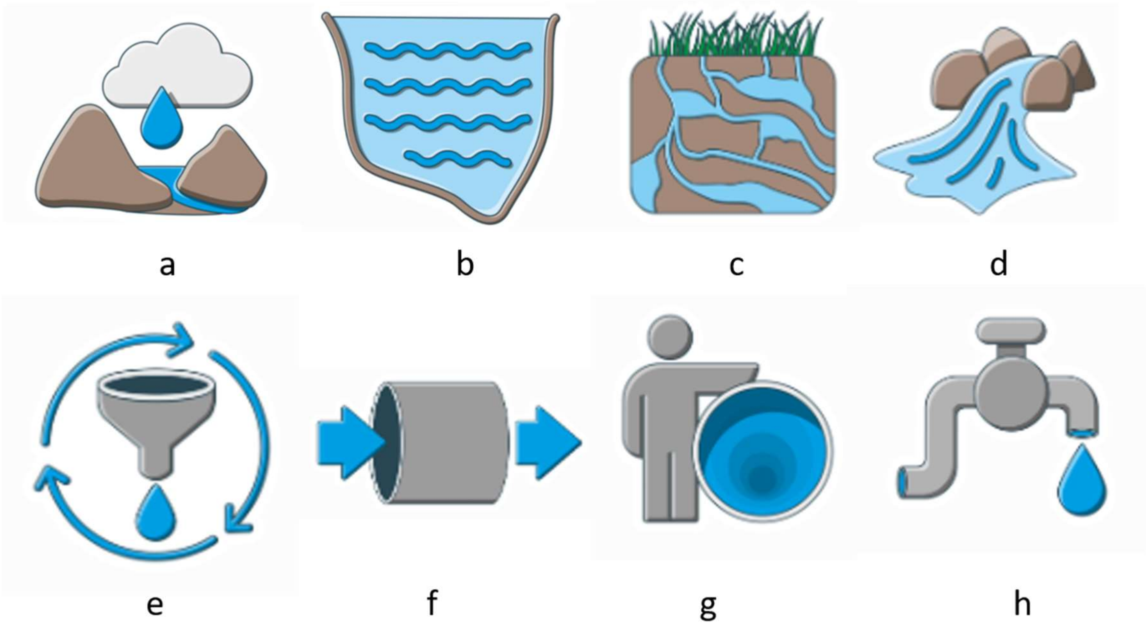


Figure 4-3. The Section 2 of INOPIA toolbar

The INFLOW element is displayed in the Figure 4-3a. The INFLOW element simulates monthly surface runoff based on precipitation anomalies, represented by the standardized precipitation index SPI (McKee, 1993). SPI is a statistical indicator comparing the total precipitation received at a particular location during a period of n months with the long-term rainfall distribution for the same period of the time at that location. SPI is calculated on a monthly basis for a moving window of *n* months, where *n* indicates the rainfall accumulation period, which is typically 1, 3, 6, 9, 12, 24 or 48 months (Climate ADAPT, 2022). The element is based on multi-regressive inflow-outflow model called SPI-Q (Romano et al., 2017; Romano et al., 2018). Such built-in model is a generic parsimonious rainfall-discharge model based on multi-regression on Standard Precipitation Index (SPI) (Romano et al., 2017; Romano et al., 2018). The common baseline is usually limited by the discharge observations, which should ideally contain 20 to 30 years of data. In case the inflow is directly connected to a reservoir, the amount of surface inflow into the reservoir can be estimated based on the difference between the reservoir volume and the reservoir discharge, also considering evaporation from the free surface. INFLOW elements are calculated using the multi-regression model SPI-Q, which is calculated as follows (Romano et al., 2017; Romano et al., 2018):

$$Q(m_i) = a_0(m) + \; a_{SPI1}(m) + SPI1(m_i) + a_{SPI3}(m) + SPI3(m_i) + a_{SPI6}(m) + \; SPI6(m_i) \quad (1)$$

where,

- $Q(m_i)$ denotes the inflow for month m and year I;
- SPI1, SPI3, and SPI6 denote standardized precipitation indices for 1, 3 and 6 months respectively;
- a_{SPI1}, a_{SPI3}, and a_{SPI6} denote the coefficients obtained by multilinear regression in relation to SPI1, SPI3, and SPI6.

The choice of the time scale of 1, 3 and 6 months is due to the different duration of hydrological processes in nature that can affect the total amount of inflow into the reservoir. SPI1 represents natural processes with fast response times such as surface runoff. SPI3 is a natural process that affects the amount of inflow into the reservoir and lasts longer than a month i.e., soil moisture. SPI6 represents slow natural processes such as melting snow and the impact of groundwater flow.

The RESERVOIR element is displayed in the Figure 4-3b. The element simulates the capacity of the surface accumulation. A feature of this element is that it remembers the evolution of the volume of water over time stored in a surface reservoir on a monthly scale. The reservoir can be artificial or natural. The element is based on the calculation of mass balance, i.e., volume. Mass balance is defined by the input data of one or more INFLOW and SPRING elements, as well as the storage capacity of the reservoir, the maximum reservoir volume, the dead volume, and each monthly release defined by the environmental flow. Dead volume is the volume of water stored below the lowest discharge level (minimum supply level). Ecological flow is a minimum flow supporting the freshwater ecosystem that depends on it.

The mass balance of the RESERVOIR is calculated as follows (Romano et al., 2017):

$$V(t) = V(t-1) + \textstyle\sum_j Q_{IN}(t,j) - \; \sum_u SUP(t,u) \quad (2)$$

where,

- t denotes time;
- $V(t-1)$ denotes the volume stored at the end of the previous month;

- $Q_{IN}(t,j)$ denotes the total inflow to the reservoir relative to the current month;
- $SUP(t,u)$ denotes the volumes distributed by the RESERVOIR to all USER connected.

The WELLS element is displayed in the Figure 4-3c. The WELLS element simulates the behaviour of a wells-field pumping from a groundwater body in terms of the monthly maximum pumping rate that can be extracted from the groundwater body. It does not represent a storage term, but the maximum volume that can be extracted from the wells by pumping, regardless of the physical reasons of wells for limitation (i.e., hydraulic conductivity of the aquifer, limits of the pumps, license constraints, limits of the dimensions of the pipeline, sea water intrusion for coastal aquifer etc.). The wells element does not use complex parametrization of soil and groundwater hydrology. The value is defined by the user for each month based on maximum volume that can be extracted from groundwater body.

The SPRING element is displayed in Figure 4-3d. The SPRING element represents a surface natural discharge from an aquifer. The element simulates spring discharge based on precipitation anomalies, represented by the SPI. The amount of spring discharge is estimated based on the precipitation anomalies. SPRING elements are calculated using a simple regression model, avoiding multicollinearity among SPI time scales, as follows (Romano et al., 2017):

$$Q(m_i) = a_0(m) + a_{SPIX\tau}(m) * SPIX(m_i, \tau) \quad (3)$$

where,

- $Q(m_i)$ denotes the discharge for the month m, year I;
- $a_{SPIX\tau}$ and a_0 denotes the coefficients from the regression;
- $SPIX(m_i, \tau)$ denotes the standardized precipitation indices for the month m, year I based on the cumulative precipitation at X months with tea delay (varying between 1 to 24);
- τ is the infiltration delay – SPI lag (varying between 0 to 6 months).

When adding SPRING, user needs to indicate firstly a precipitation file with one or more monthly cumulated precipitation time series [mm] and secondly a discharge file with observed discharge. Single precipitation time series needs to have at least one value for each month of the simulation timeline. For fair calibration for discharge, 15-20 years of observations are necessary.

The ALTERNATIVE WATER RESOURCES is displayed in the Figure 4-3e. This element gives the user the ability to implement non-conventional water resource characterized by a maximum volume that can be distributed monthly (similarly to the WELLS element). The difference is that the element of alternative sources simulates the use of water from resources such as a purifier, a desalination plant defined by the maximum flow determined by the concession rules and varies from state to state. User defines the input data.

The CONNECTOR element is displayed in the Figure 4-3f. The INOPIA user uses the CONNECTOR element to connect resources and users. Basically, it displays a blue arrow from the resource to the user in the water supply scheme, see Figure 6-6. The element must always be directed as the water flow, i.e. from the resource to the user.

The MANAGEMENT NODE is displayed in the Figure 4-3g. The MANAGEMENT NODE is a crucial element of INOPIA. User of INOPIA, through this element is entering all the information necessary for addressing needs in water supply scheme. While building a water supply scheme just with one resource and one user, user of INOPIA doesn't need to use MANAGEMENT NODE. In that case, all the available water is going towards one user.

The case is different if user of INOPIA has more or resources or users in water supply system scheme.

The user of INOPIA will use MANAGEMENT NODE when one of these cases occurs: single-resource-multi-user, the multi-resource-single-user or multi-resource-multi-user.

In Figure 4-4. Single-resource-multi-users scheme is presented.

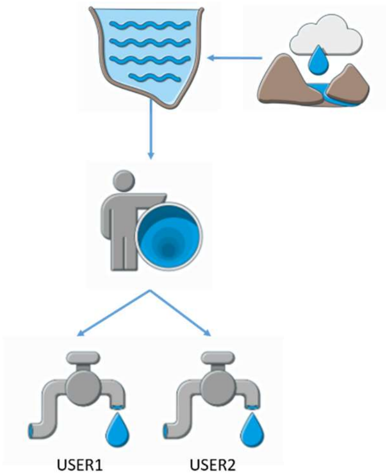


Figure 4-4. Single-resource-multi-user scheme

In the single-resource-multi-user water scheme displayed in Figure 4-4., each user element is characterized by a monthly water requirement. Before building a scheme user of INOPIA is giving a priority to users, depends of area, laws etc. Water can be used for drinking, irrigation, industrial use etc. The requirement of water in this scheme is sum of requirement of USER1 and USER2. The total requirement is addressed to the reservoir as a single resource. In a case when a single resource has enough volume of water to satisfy needs of users, there will be no deficit. But if, demand for water is higher than availability of water, there will be a deficit.

In Figure 4-5. Multi-resources-single-user scheme is presented.

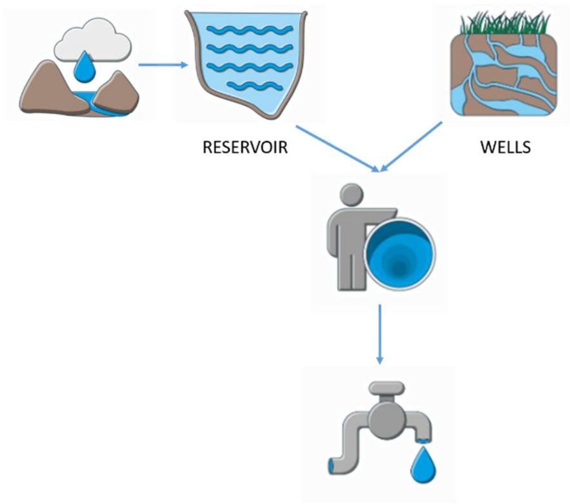


Figure 4-5. Multi-resources-single-user scheme

In the multi-resource-single-user water scheme, more resources are connected to one USER. The total availability of water is sum of availability of water of each resource.

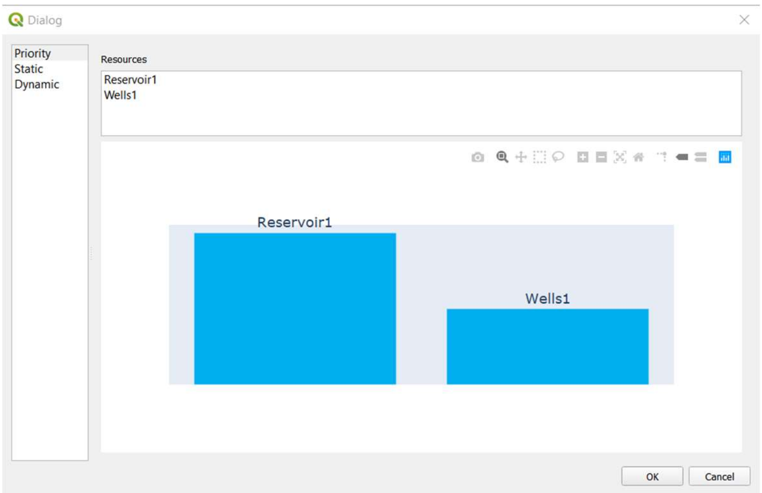


Figure 4-6. MANAGEMENT NODE framework

In this example, the user of INOPIA, while building a scheme, is giving a priority using MANAGEMENT NODE. In this case, RESERVOIR has a priority over WELLS as shown in the Figure 4-6. Figure 4-6. Shows a MANAGEMENT NODE framework.

The USER demand is firstly sent to RESERVOIR. If the demand is not fully supplied by RESERVOIR, it is send to WELLS. In this example, USERs monthly demand is 8Mm³, RESERVOIR available volume is 4Mm³ and maximum pumping rate for WELLS is 5Mm³. An 8Mm³ demand is sent to the RESERVOIR, 4Mm³ are still to be supplied. There is potential deficit of 4Mm³ in the RESERVOIR element, representing a lack of resources necessary to meet all the addressed demand. As the USER will address the remaining demand to the next resource in the priority list, this deficit is considered potential, as it is not an actual deficit for the USER nor for the WSS. Remaining -4Mm³ demand is sent to the WELLS element, for which 5 Mm³ of volume is currently available. Total demand of USER is supplied by RESERVOIR and WELLS and there is no deficit.

In the event that the last element in the priority list does not have sufficient resources to meet the demands of the users, there would be a real deficit in the water supply system scheme.

In Figure 4-7. Multi-resources-multi-users scheme is presented.

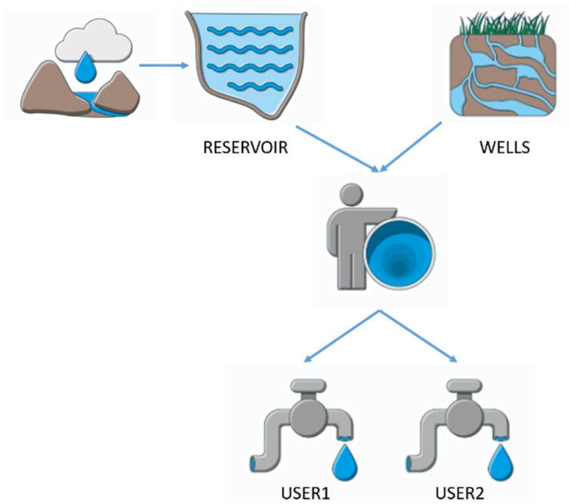


Figure 4-7. Multi-resources-multi-user scheme

Using this element, user set priorities in the water scheme. The user creates a water scheme with more resources and more users. Using this element, user enter the necessary data needed to determine the potential deficit. More about this element will be shown below in the example of the water scheme of the city of Foligno.

The USER element is displayed in Figure 4-3h. The element represents all possible water users supplied in a generic water supply scheme. The USER element can be a user of drinking water, irrigation water, water for industrial use, hydroelectric power plans. User determines the level of user priority using management nodes. When creating a water scheme, one number will be displayed on this element. The number will be displayed in the blue drop of the element and will indicate the priority level. INOPIA gives the user the opportunity to determine the priority level of USER, it may depend on the region/country.

The third section of the INOPIA toolbar shows data editing tools on Figure 4-8.

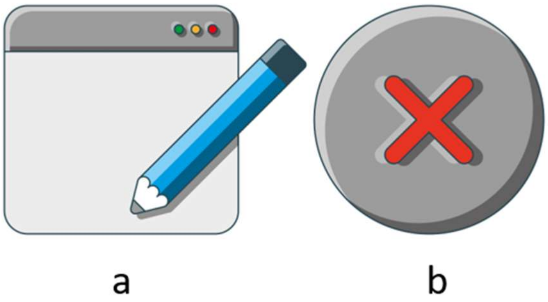


Figure 4-8. Section 3 of INOPIA toolbar

The EDIT tool is displayed in the Figure 4-8a. By clicking on the edit tool, the user must click on the element he wants to change. This option has a different effect for each INOPIA element. For the management node element, this tool allows to change user priorities or transfer new files for the INFLOW or RESERVOIR element. Every change is automatically saved.

The element DELETE is displayed in the Figure 4-8b The element allows deleting and/or modifying topological elements.

The fourth section of the INOPIA toolbar shows the tools for data processing and post-processing.

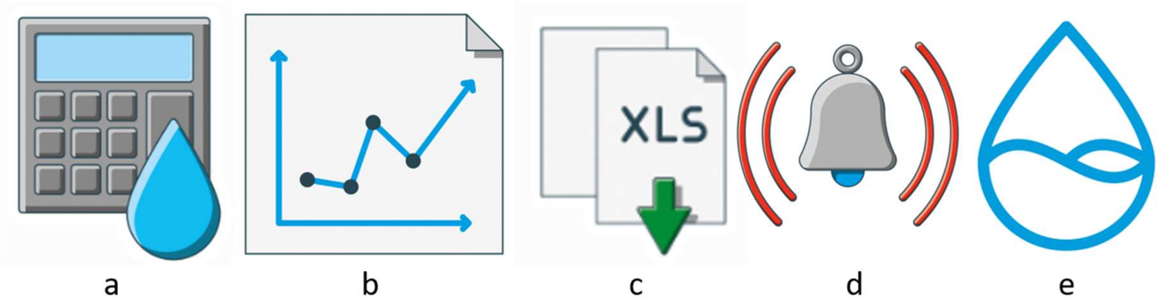


Figure 4-9. Section 4 of INOPIA toolbar

The RUN element is displayed in Figure 4-9a. The element allows the "RUN" option. Its task is to process a set of data. The data were previously implemented in a topological scheme with all the rules and precipitation data. By clicking on the "RUN" option, the user selects a time frame for data processing. INOPIA proposes dates with the maximum availability of data implemented in the scheme.

The PLOT element is displayed in the Figure 4-9b. The element is part of the post-processing tool. The PLOT tool allows the user to view graphs related to the output of each element of the implemented topological scheme except the management node. By clicking on the "PLOT" option, the user must select the element that interests him.

The EARLY WARNING for spring and reservoir tool is displayed in the Figure 4-9c. This tool helps the user in early warning decision support. EARLY WARNING icon allows the user to view previous element deficits. Based on the relationship between observed precipitation anomalies and simulated deficit, it approximates the relationship between meteorological drought and water safety. For a given month of the year, it assumes that based on the precipitation anomalies of the previous months, one can partially predict the occurrence and intensity of a possible deficit (as a measure of how much a deficit can impact water safety) in the coming months.

The XPORT TO XLSX tool is displayed in the Figure 4-9d. This tool allows the user to export the data available for each element of the topological scheme in Excel format. After clicking on this icon, the user must select the element he is interested in and indicate the name of the file in which the information available for a particular element is entered. This option allows the user to post-process the output out of INOPIA.

The icon of INOPIA is displayed in the Figure 4-9e. The element represents the INOPIA tool logo. Clicking on the icon opens a website with all the information about the INOPIA tool. The user of the INOPIA tool can find all the necessary data by clicking on this icon as well as the user manual (http://inopia.gitlab.irsa.cnr.it/inopia-docs/preamble.html).

4.4. Input data of topological elements

The input data required for the creation of the water supply scheme are entered into the already defined Excel spreadsheets. Table 4-1. shows the input data for each element needed to create the scheme. Excel spreadsheets can be found on the official INOPIA website, which is also used as a user manual (http://inopia.gitlab.irsa.cnr.it/inopia-docs/).

Table 4-1. Input data required to create a water scheme

Element	Input data
INFLOW element	• Monthly precipitation data [mm] • Inflow data on a monthly basis Q [m^3 / s]
RESERVOIR element	• Data on maximum, minimum, dead volume, and ecological flow [m^3 / s]
WELLS element	• Maximum monthly exploitable volume [m^3 / s]
SPRING element	• Monthly precipitation data [mm] • Monthly spring discharge Q [m^3 / s]
ALTERNATIVE RESOURCE element	• Maximum monthly exploitable volume [m^3 / s]
USER element	• Monthly water demand [m^3 / s] • User priority level

5. UMBRIA REGION

5.1. Geological characteristics

The city of Foligno is located in the central part of the eastern Umbra Valley in the Umbria region. Umbra Valley is residue of the south-eastern part of the Plio-Pleistocenic Tiberino basin. A wide depression, Umbra Valley, is characterized by very low declivity, creating difficulty with drainage. Over the last three millennia, this zone has alternately partially or totally flooded and dried, with lakes and marshes, or sometimes been quite dry and easily accessible by man. There were three causes of variation from totally flooded to dried: a) climate change, with changes in rainfall; b) tectonic movements causing in an increase or decrease in outflow thresholds; and c) man attempting to lower the threshold and canalize streams and creeks to reclaim land. The tectonics of Central Italy during the Late Miocene-Pliocene was characterized by compressive phases that caused the uplifting of several NNW-SSE mountain ridges, progressively younger from West to East. Grabens and depressions were created by tensile-relaxing movements that followed each phase (Ambrosetti et al., 1987).

Between Late Miocene/Pliocene and Pleistocene age, Umbria was characterized by compression-tension sequences. The result was a 140 km-long depression that crossed the entire region from north to south. A high ridge on the east side (Mt. Nerone, Mt. Catria, and Mt. Brunette) prevented the water outflow towards the Adriatic Sea. As a result, the Umbrian depression began to flood and became a lake basin, known as the "Grande Lago Tiberino", or "Tiberino Basin" more properly. In Figure 5-1. Central Italy structural scheme during Pliocene with NW-SE trending ridges and the interposed basins is presented. The scale of the Figure 5-1. is 1:1400000 (Colacicchi, 1992).

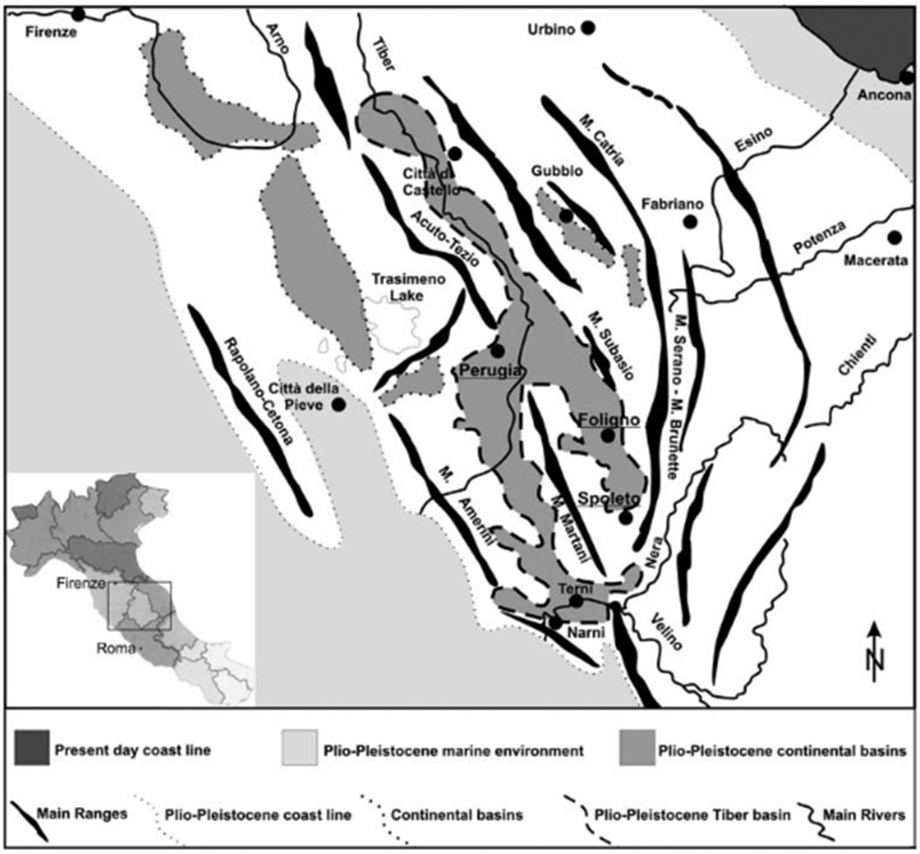


Figure 5-1. Central Italy structural scheme during Pliocene with NW-SE trending ridges and the interposed basins (Colacicchi et al., 1992)

Near the City of Perugia, Tiberino Basin splits in two arms, one of which is the western Valle Amerina and the second one is eastern Valle Umbra. The morphological situation of the Umbra valley is characterized with a depression oriented in the SSE-NNW direction. On the east side are Mountain Subasio and a ridge with mountain Brunette and on the west side is Mountain Martani (Colacicchi et al., 2008).

The valley bottom is characterized by the lacustrine and fluvial deposits. Deposits made of clay interbedded with sandy level, scattered conglomerates, palaeosoils and lignite beds. Some deposits are hundred meters thick and are evidence of tectonic subsidence. Except for tectonic subsidence, lacustrine environment with lateral tributaries carrying sediments is also proof of tectonic subsidence. The morphological aspect of the valley was mostly controlled by mild periods, characterized by high temperature and limited rainfall, alternating with critical periods with low temperature and high precipitation. There were also other factors which influenced the morphological aspect of the valley, and they are: tectonic movements, active until Late Pleistocene, causing the depression of the valley flat and rising both the valley sides. Also, the action taken by the inhabitants to deepen the outflow threshold to accelerate the water's drain off and digging the canals. A geological map of valley Umbra is presented in Figure 5-2 (Colacicchi et al., 2008).

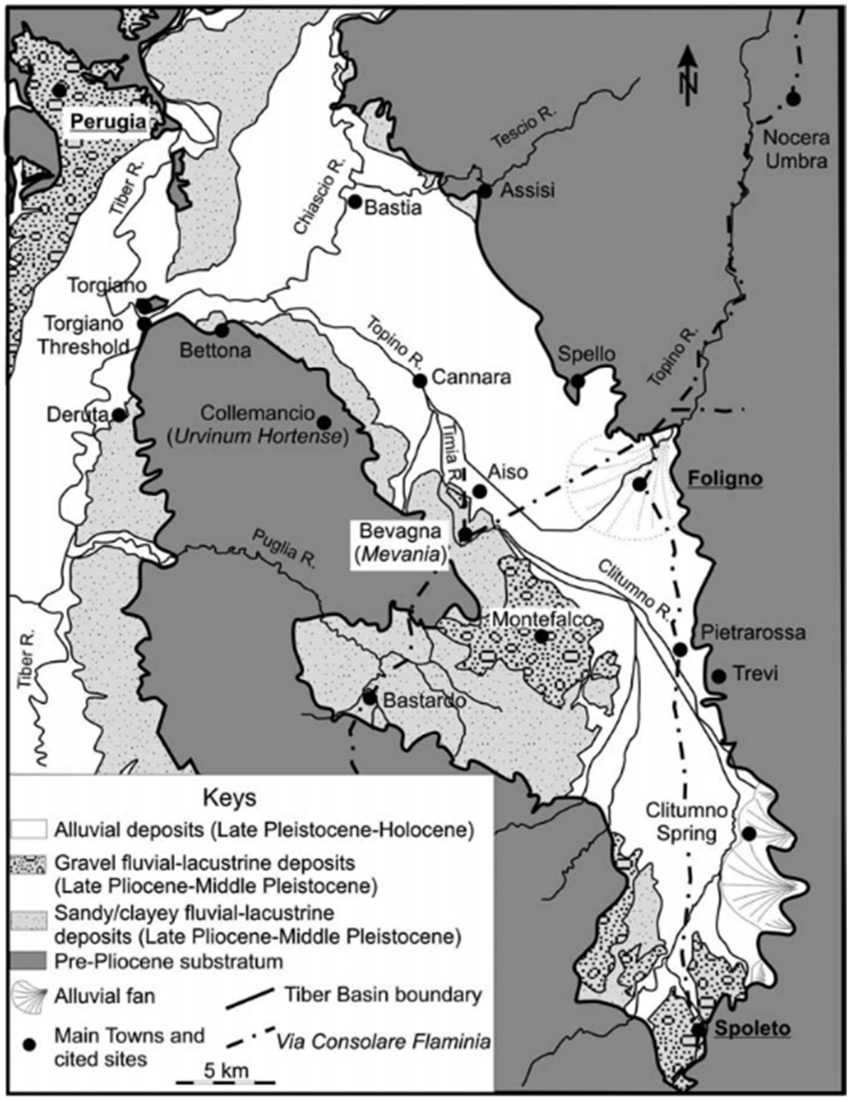


Figure 5-2. Geological map of valley Umbra (Colacicchi et al., 2008).

5.2. Climate variations in Umbria

In the Figure 5-3, climate variations for the last three thousand years are presented. The curve has been synthesized from several data collected from pollen analysis, ice cap oscillations and historical data for the last two thousand years and lake level variation (Brugiapaglia et al., 1995).

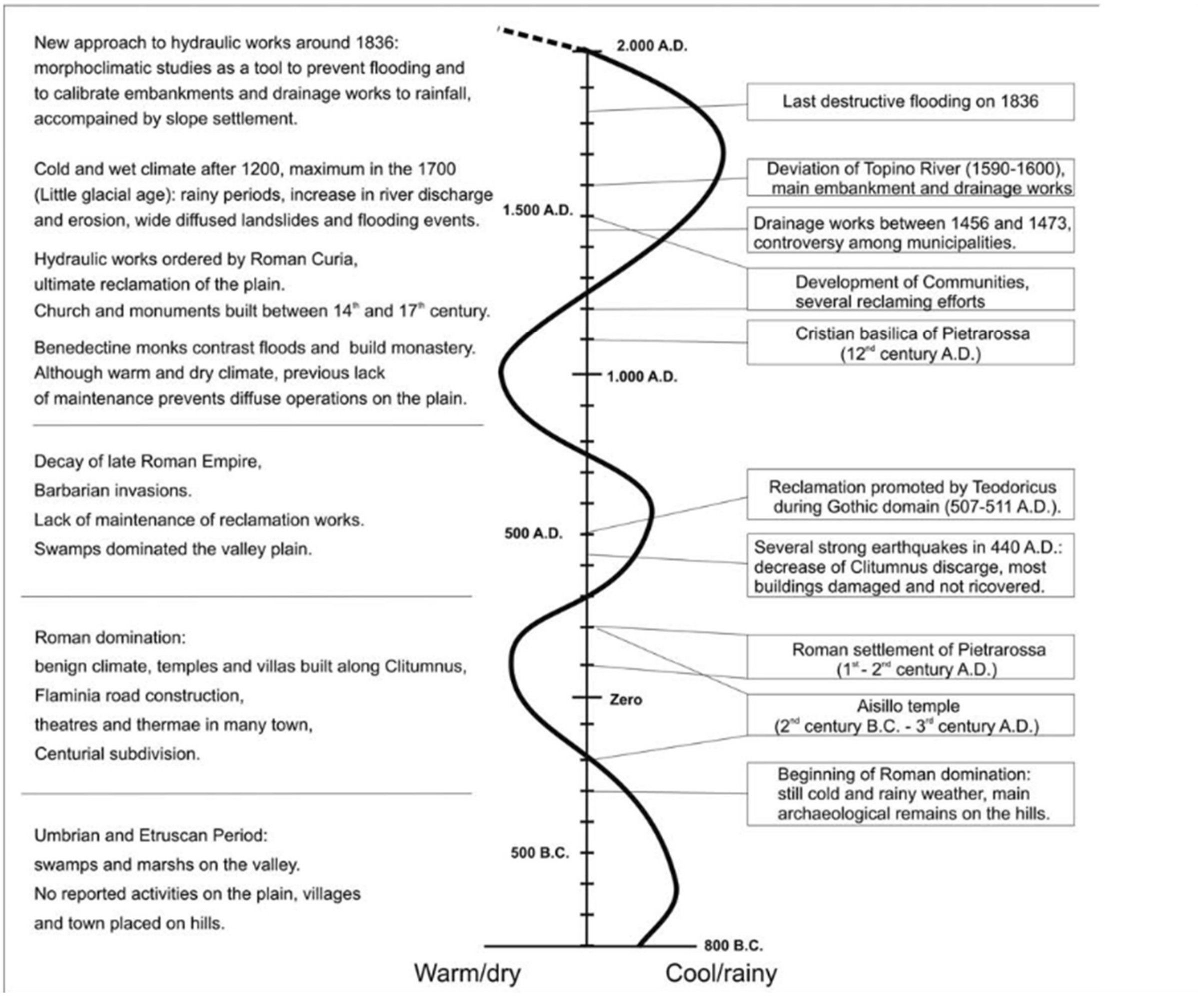


Figure 5-3. Climate variations for the last three thousand years of Umbra Valley (Brugiapaglia et al., 1995)

A "climatic optimum" followed the last glaciation in the period before 1000 BC and continued until 900 BC. A climate was warm and dry. This period does not have any documents or data about the valley floor, so they cannot be considered. In the period from 900 BC to around 250 BC, a cold and rainy climate, were documented by glacial expansions and retreats. The following period was warm and dry and lasted from 250 BC to the third century AD. Information for this period of Roman domination came from archaeological remains. The cold medieval phase, documented by historians lasted between 200 and 800 AD. Afterward the warm phase which lasted until around 1250 AD, there was a short, but intense cold phase called the Little Ice Age (LIA) from 13000 to 1850, which led to the current climate. The morphology of the valley was influenced by climate oscillations, at the same time as local populations lived in the valley and left traces (Brugiapaglia et al., 1995).

Lazio borders the region to the south, Marche borders it to the east, and Tuscany bordered it to the west. In the western area, near the Tuscany border, Umbria receives an average annual precipitation of 800 millimeters (lower than Italy's average annual precipitation of about 1050 millimeters) and 1300 millimeters (higher than Italy's average annual precipitation), along the Umbria-Marche Apennines in the eastern region based on recent data from 2011. (Vergni et al., 2011).

5.3. Hydrogeological characteristics

Among the most important groundwater resources in Italy are the karst carbonate aquifers of the Central Apennines. Also, the hydrological complexes of Umbra Valley mainly contain shallow aquifers.

Carbonate aquifers, formed in karstic environments in Umbria-Marche Apennines, east of Umbra Valley, are a result of the dissolution of carbonate and limestone rocks. This area is karst, which results in rapid water infiltration, leading to shortage availability of surface waters. In this region, karst aquifers are important and high-quality groundwater resources that can be used both for agriculture and for drinking. Additionally, these aquifers have a vital role in regulating the hydro-ecological regime of surface waters and rivers (Allocca et al., 2014). There are several processes that affect water balance, such as the outflow from springs. The processes are evapotranspiration, infiltration, surface runoff, and lateral inflows. These processes are caused by underground outflows as well as changes in aquifer capacity. In recharge areas, these processes regulate the transition from precipitation to spring discharge (Raju et al., 2011). In the eastern and southern parts of the Umbria-Marche Apennines, the limestone hydrogeological complex is characterized by several springs draining water from aquifers stored in carbonate formations.

In Figure 5-4. Umbria hydrogeological complexes, springs and rain gauges are presented.

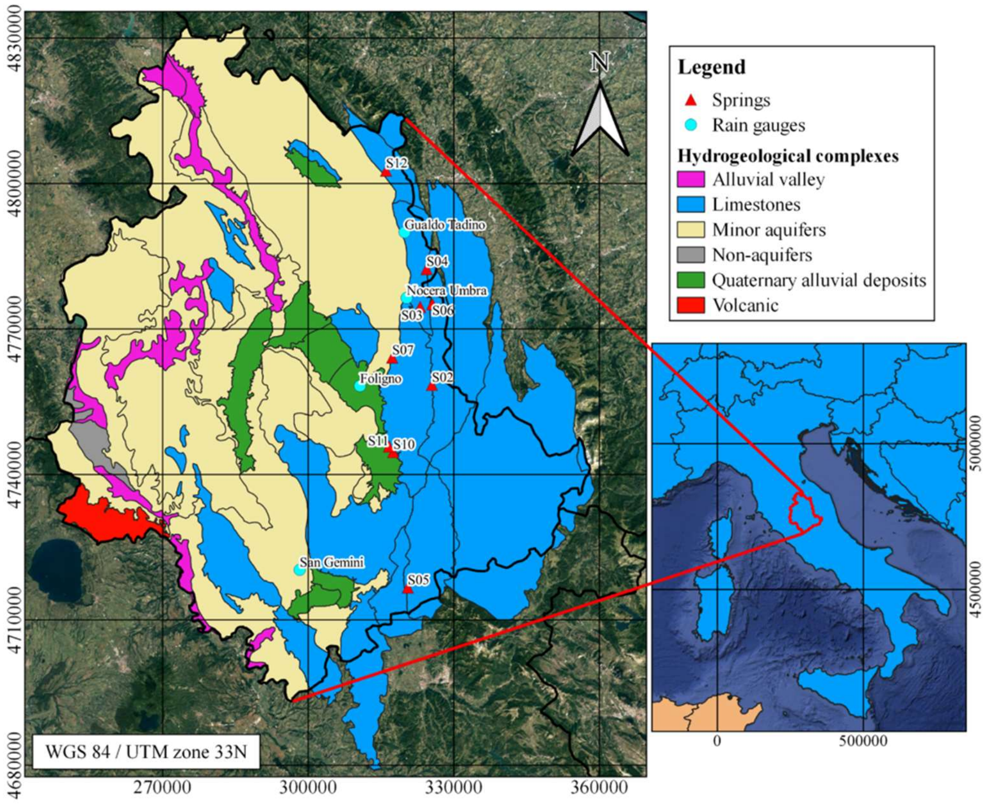


Figure 5-4. Umbria hydrogeological units springs and rain gauges (Allocca et al., 2014)

5.4. Distribution of water resources among users

The region of Umbria belongs to Central Italy. As mentioned in the previous chapter, the average precipitation in the Umbria region is around 950 mm/year, which is about 26.2% of the total annual precipitation in Italy. In Table 5-1. the distribution of renewable and usable resources (in Gm^3) in the region of Umbria is shown.

Table 5-1. The distribution of renewable and usable resources in the region of Umbria. Source: (ANPA, 2001)

Region	Exploitable surface waters [Gm^3]	Exploitable ground waters [Gm^3]
Umbria	5,4 (13,6%)	7,8 (15,1%)
Italy	39,7 (100%)	51,8 (100%)

Water is used by the agricultural sector 60%, the energy and industrial sectors 25%, and the civil sector 15%. After the United States and Canada, Italy has the highest per capita water consumption in Europe, but with extremely variable values that range from 150 to 400 liters per day. Among the most concerning data is the estimated 40 percent loss in distribution networks, both for drinking water and irrigation (Sappa et al., 2001).

6. EXAMPLE FOLIGNO

For the purposes of this thesis, a water supply system scheme was developed in INOPIA for the City of Foligno. The City of Foligno is located in the region of Umbria, in the province of Perugia in central Italy. The Figure 6-1. shows the region of Umbria in green on a map of Italy (Melelli, 2019).

Figure 6-1. Location of Umbria region (Melelli, 2019)

In the Figure 6-2 the region of Umbria is shown on a larger scale with the exact position of the City of Foligno marked with a blue underline.

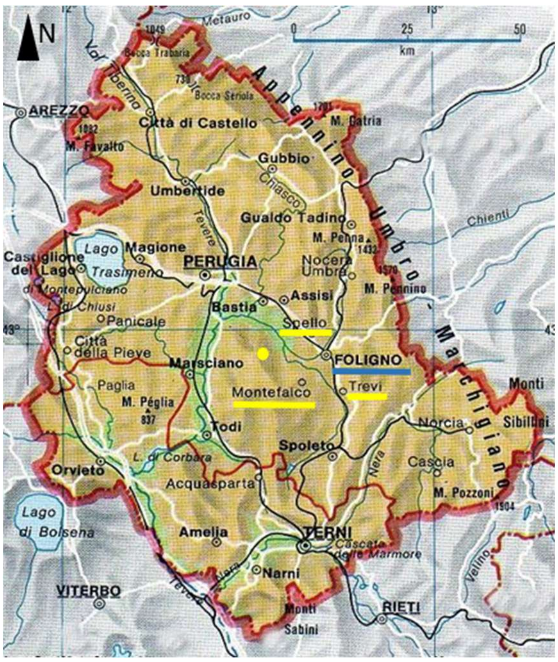


Figure 6-2. The city of Foligno in the Umbria region marked with a blue underline (INFORMA GIOVANI ITALIA, 2022)

The map also includes smaller towns located in the vicinity of the city, namely: Spello, Trevi, and Montefalco marked with yellow underline. The water supply system scheme of Foligno includes also City Bevagna marked with yellow point on a map. The number of inhabitants of these towns and cities is shown in the Table 6.1. The data are valid for 2017. (CITY POPULATION, 2017)

Table 6- 1. Population of Foligno in 2017 (CITY POPULATION, 2017)

City	Number of inhabitants (2017)
Foligno	57 164
Spello	8 579
Trevi	8 372
Montefalco	5 626
Bevagna	5 068

6.1. Input of Foligno water supply system scheme

The scheme of the Foligno water supply system was created using 5 different topological elements, namely: user, connector, wells, management node, and spring element. The water supply system scheme of Foligno was made using these elements because they are interconnected and interdependent, and those are:

- Wells: Wells Cantone, Wells San Pietro 1 e 2, Wells Vene del tempio and Wells Capadacqua di Foligno and Acquabianca;
- Spring: Rasiglia Alzabove;
- Users: city of Foligno, towns: Spello, Trevi, Montefalco and Bevagna.

The demand of drinking water in this system is a demand of drinking water of 5 different categories of users. Each user represents a town with its needs for drinking water through a year. Each user is supplied by water from four pumping stations (represented through the WELLS element) and one spring. The following is the input of data used to create the water scheme:

- Wells input:

Table 6-2. Wells input

Wells Cantone	Maximum withdrawals 45 l/s (constant throughout the year)
Wells San Pietro 1 e 2	Maximum withdrawals 70 l/s (constant throughout the year)
Wells Vene del tempio	Maximum withdrawals 50 l/s (constant throughout the year)
Wells Capodacqua di Foligno and Acquabianca	Maximum withdrawals 160 l/s (constant throughout the year)

- Spring input: Rasiglia Alzabove spring. Input is a daily precipitation data measured from January 1951 to October 2021 presented in Figure 6-3, and monthly inflow data measured from January 1998 to November 2021 is presented in Figure 6-4. Data source: ARPA UMBRIA, 2022

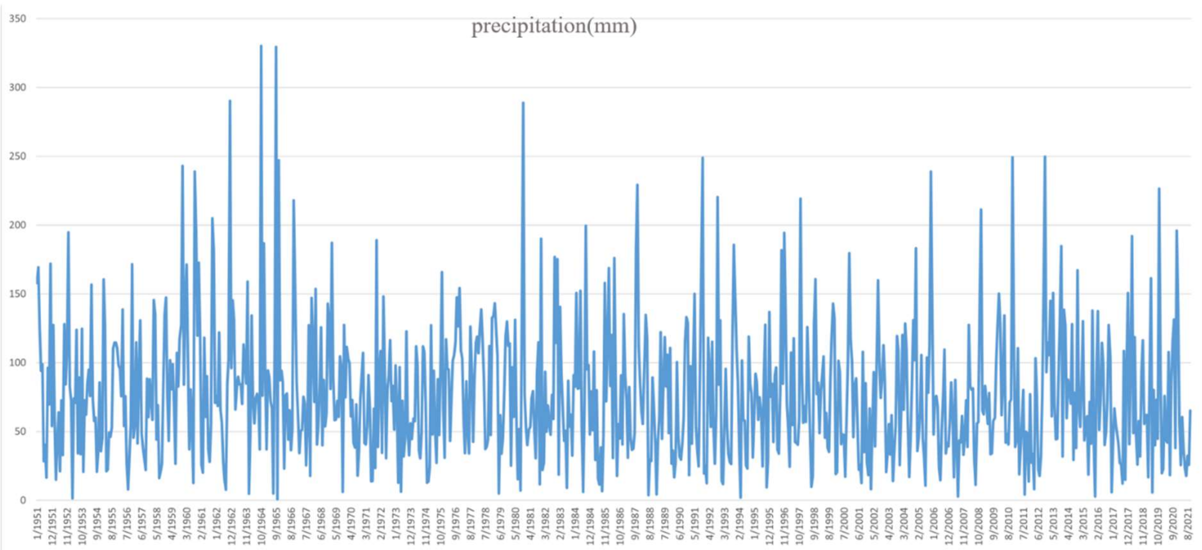


Figure 6-3. Daily precipitation data measured from January 1951 to October 2021 for Rasiglia Alzabove (ARPA UMBRIA, 2022)

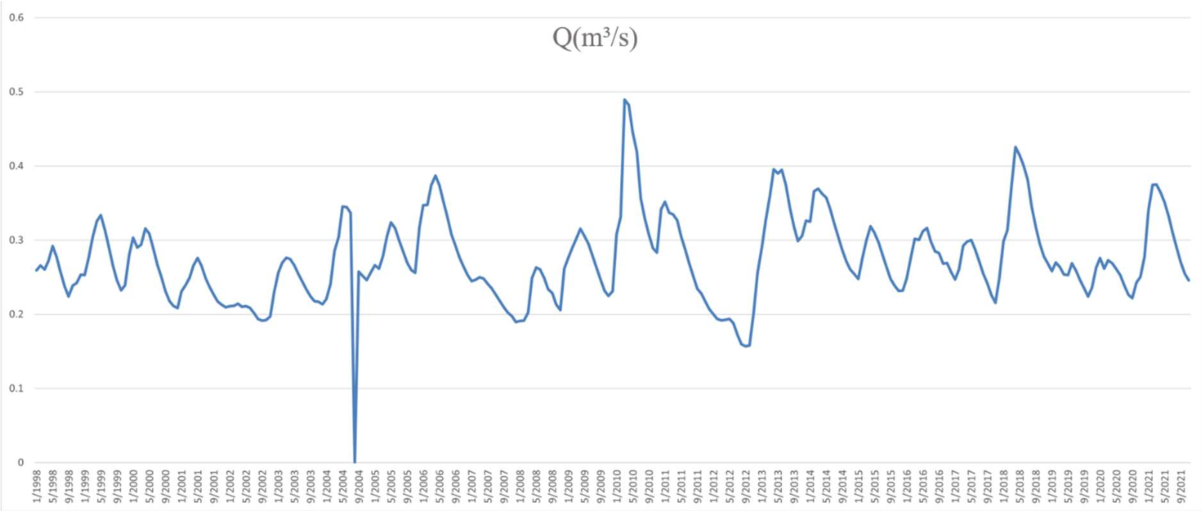


Figure 6-4. Monthly inflow data measured from January 1998 to November 2021 for Rasiglia Alzabove (ARPA UMBRIA, 2022)

In Figure 6-5. the needs of each user are shown on a monthly basis.

- Users input:

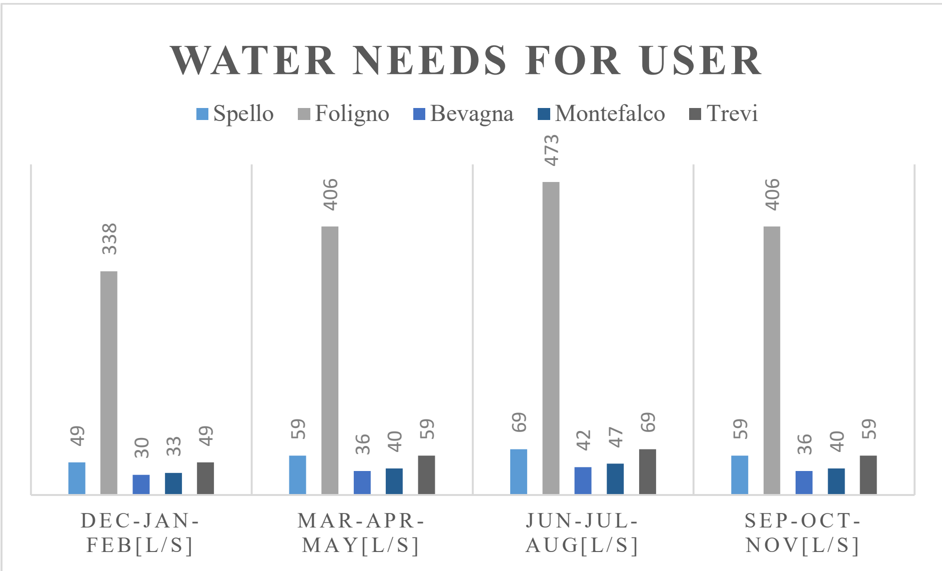
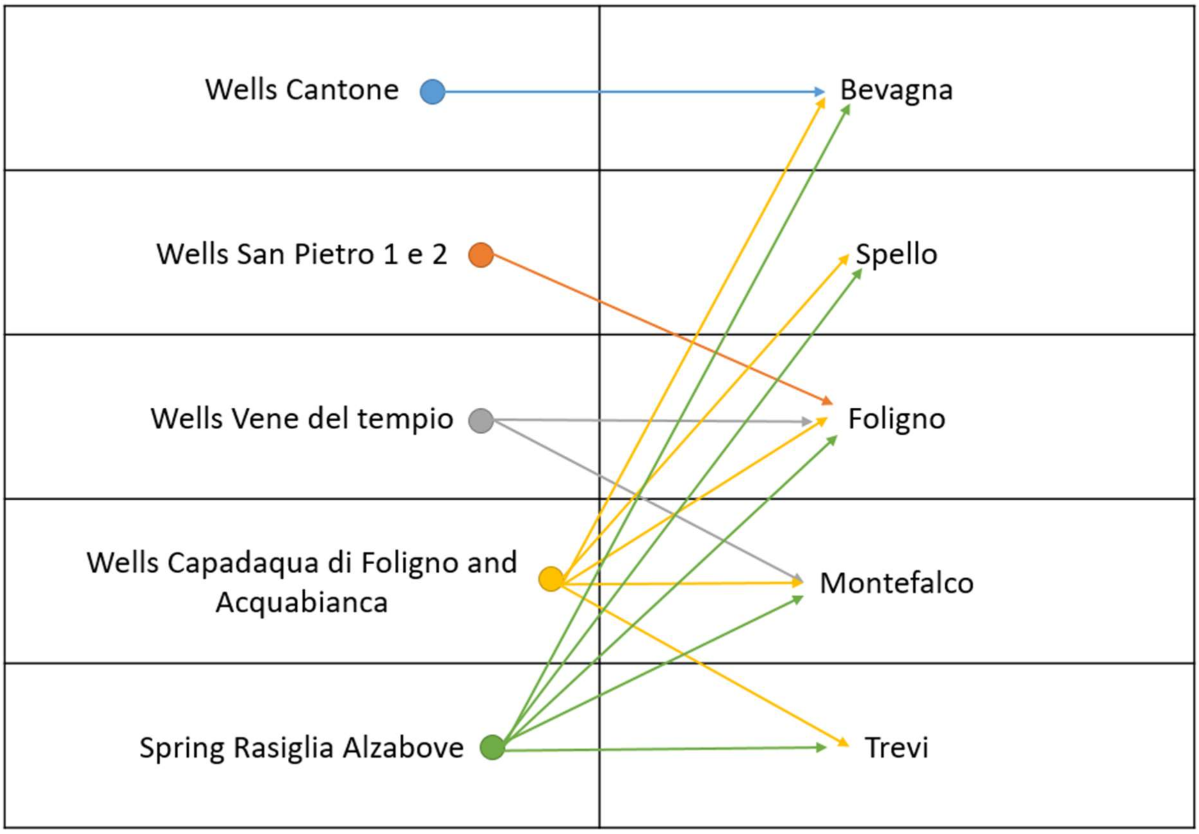


Figure 6-5. The needs of each user on a monthly basis (Regione Umbria – Assemblea legislative, 2006)

All users (city Foligno, towns: Spello, Trevi, Bevagna and Montefalco) have a need for drinking water and have the same priority. Drinking water supply management concept is showed in the Table 6-3:

Table 6- 2. Drinking water supplies management concept



Water supply system scheme of Foligno shown in Figure 6-6. was made following several rules. The first rule is: each USER has the same priority, because each USER is represented as drinking water demand. Each user is connected to one or more resources to meet the monthly water demand for the user. Resources Wells Acquabianca and Capodacqua di Foligno and Spring Rasiglia Alzabove are common to each USER on this scheme as shown in the Table 6-3. Wells Cantone is supplying only one USER, the same is for Wells San Pietro 1 e 2 as shown in the Table 6-3. Wells Vene del tempio is supplying two USERS as shown in the Table 6-3. Priorities are set using the MANAGEMENT NODE.

A management scheme of the water supply system of the city of Foligno and its surroundings was made, the scheme is shown in the Figure 6-6.

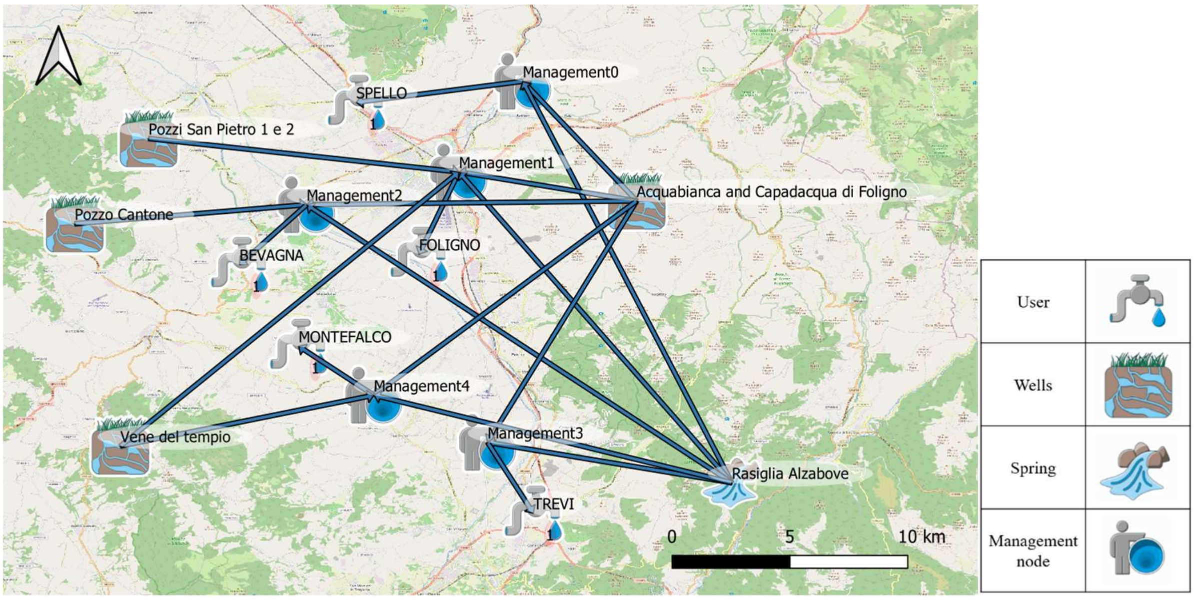


Figure 6- 6. Water supply system of the city of Foligno

To determine the priorities needed in a possible water crisis, user uses the management node. In this case, a multi-resources-multi-users scheme is presented.

While building a water supply scheme of city of Foligno, resource priorities are in the range of one to three. In a case of possible water crisis, using the management node, Rasiglia Alzabove spring was given priority 3 for all users, joint Wells Acquabianca and Capodacqua di Foligno priority 2, and the remaining wells priority 1, depending on the user. All users of this water supply scheme share Spring Rasiglia Alzabove and Wells Acquabianca and Capodacqua di Foligno. Meaning, distribution of water of Bevagna user: The demand for water starts from the resource Wells Cantone, which has priority 1. If the user's needs cannot be met, the demand is directed to the resource with priority 2, which is Wells Acquabianca and Capodacqua di Foligno. If even then the needs of the user Bevagna are not met, the request goes to the resource with priority 3, which is Spring Rasiglia Alzabove Resources associated with a particular user have higher priority than shared resources. This distribution of priorities relieves the common resources which are Wells Acquabianca and Capodacqua di Foligno and Spring Rasiglia Alzabove.

6.2. Output of Foligno water supply system scheme

6.2.1. Rasiglia Alzabove spring output

Plot element diagnostic applied to each single element and each run (except the management node). After selecting the "plot element diagnostic" icon, the user clicks on the element to be displayed, and selects an available run to generate the figure. In the Figure 6-7. Spring Rasiglia Alzabove plot element diagnostic is shown.

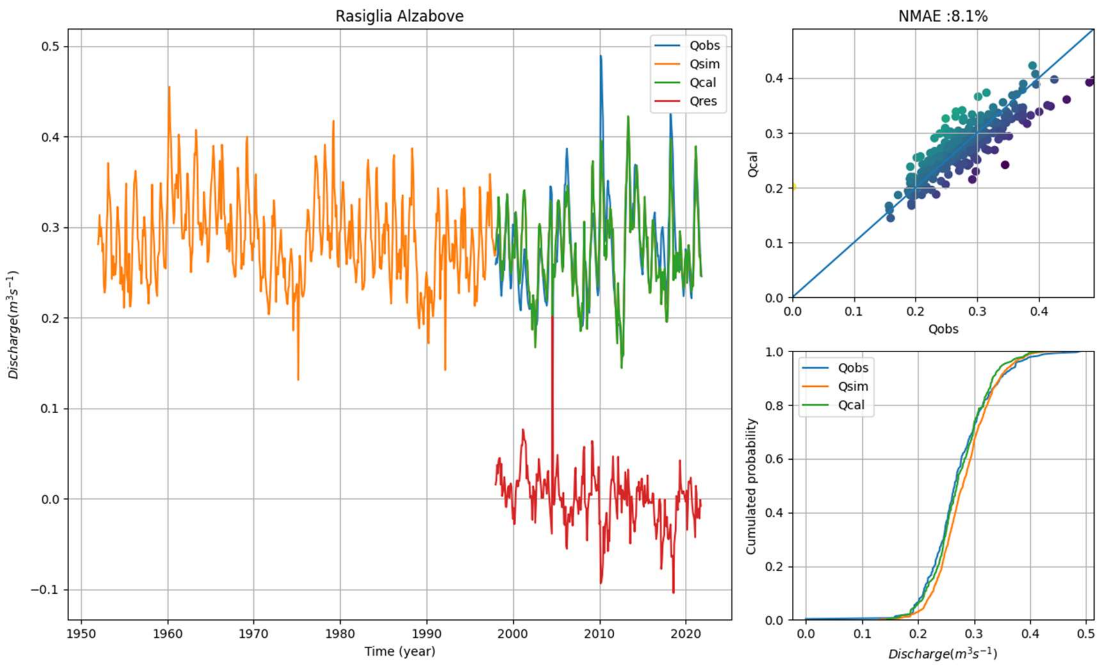


Figure 6- 7. Plot element diagnostic applied to spring Rasiglia Alzabove

The left graph in the Figure 6-7. shows the time series the observed runoff (Qobs) in blue, the simulated data based on precipitation anomalies (Qsim) in orange, the calibration data (Qcal) in green and red shows the difference between Qobs-Qcal (Qres). This upper right chart shows Qcal with respect to Qobs. Normalized mean absolute error (NMAE) at the top of the graph of 8.1% is also stated. NMAE estimates the difference between the observed (Qobs) and model calculated (Qcal) spring discharge. A lower NMAE value indicates a better performance method for the imputation task. The cumulative probabilities of Qobs, Qsim, and Qcal are shown in the diagram in the lower right corner. The cumulative distribution function is used to describe the probability distribution of random variables (Aslan, 2020).

6.2.2. Output of Wells Acquabianca and Capodacqua di Foligno

After selecting the “plot element diagnostic” icon, the user clicks on the element to be displayed, and selects an available run to generate the figure. In the Figure 6-8. output of Wells Acquabianca and Capadacqua di Foligno plot element diagnostic are shown.

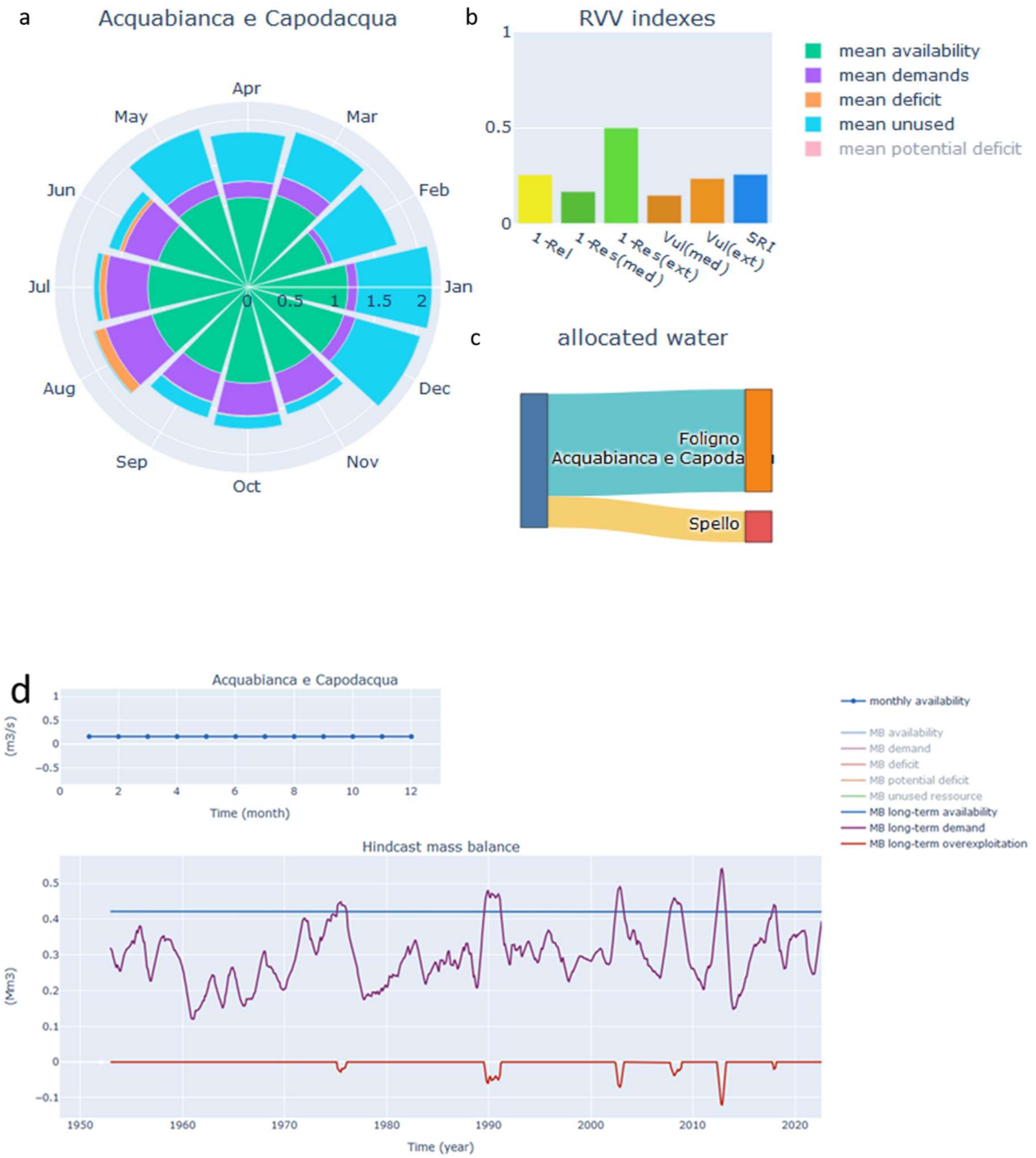


Figure 6-8. Output of Wells Acquabianca and Capadacqua di Foligno. 6-8a shows monthly mean value of the considered element. 6-8b represents the RRV(Reliability-Resilience-Vulnerability) metrics. 6-8c shows inter-element flux, considering all elements connected to the selected resource. 6-8d shows mass balance variables of the considered element in Mm^3.

The output charts of Wells Acquabianca and Capadacqua di Foligno are presented in the Figure 6-8.

The Figure 6-8a shows monthly mean value of the mass balance variables of the considered element expressed in Mm^3. In addition to selecting the variables to display, the user can also select the period (within the selected run) and month.

In this case, there is potential deficit in June, July, and August for Wells Acquabianca and Capadacqua di Foligno. This can be read from the appearance of the orange part on the chart that represents the mean deficit.

The graph presented in a Figure 6-8b shows the RRV(Reliability-Resilience-Vulnerability) metrics and the elements of the graph are explained below. This chart explains the risk of deficit of the element, in terms of occurrence probability (reliability), duration (Resiliency) and intensity (Vulnerability) indexes, following Romano et al. (2017). Based on the output from the RESERVOIR module, this analysis provides a statistical quantification of the exposure of the water system to failures by estimating the probability, duration, and intensity of water deficits (Romano et al., 2018).

- Rel (Reliability): the element is analyzed in terms of the frequency of occurrence of the inability of a given resource (in this case the Wells Acquabianca and Capodacqua di Foligno) to meet the connected water need:

$$Rel = \frac{n_s}{T} \tag{4}$$

where, *ns* is the number of satisfactory time steps (i.e., a time step during which the demand is fully satisfied); *T* is whole operation period Value of Rel is dimensionless and $0 \leq Rel \leq 1$. (Romano et al., 2018)

- Res (Resilience): the system's recovery capacity after a deficit event. Res is divided into 2 columns (Figure 6-8c), Res(med) and Res (ext). Res(med) and Res(ext) are adopted to quantify Resilience. These are the 50^{th} and 90^{th} percentile (positive tail) of the frequency distribution of the failure durations. Splitting the Resilience metric into the median and 90th percentile also allows for the consideration of events with a long return period, as suggested in the Drought Management Plan Report from the EU Commission (2008). Res is estimated based on a set of data consisting of the duration of the computed deficit. In the operation period T, they are computed based on the median (perc50) and extreme (perc90) durations of failures, normalized according to the number of months in a year (12):

$$Res_{med} = 1 - \frac{1}{12} perc_{50}\{m_f(i)\}_{i=1,\dots,N_f};\ Res_{ext} = 1 - \frac{1}{12} perc_{90}\{m_f(i)\}_{i=1,\dots,N_f} \tag{5}$$

where, *Nf* is the total number of failures during the operation period mf(i) is the duration of the i-th failure *perc*50 and *perc*90 are the 50th and 90th percentile (positive tail) of the frequency distribution of the failure durations.

Vul (Vulnerability): shows the intensity of the deficit. Vul is divided into 2 columns, Vul and Vul (ext). Vul is estimated based on a data set consisting of a deficit, standardized with respect to total demand. Medium failure rates (Vul med) and extreme events (Vul ext) are also taken into account:

$$Vul_{med} = perc_{50}\left\{\frac{\left(\sum_{j=1}^{m_f(i)} WD_{j(i)}\right)}{\left(\sum_{j=1}^{m_f(i)} Wd_{j(i)}\right)}\right\}_{1=1,\dots,N_f} ;Vul_{ext} = perc_{90}\left\{\frac{\left(\sum_{j=1}^{m_f(i)} WD_{j(i)}\right)}{\left(\sum_{j=1}^{m_f(i)} Wd_{j(i)}\right)}\right\}_{1=1,\dots,N_f} \quad (6)$$

where, *Nf* is the total number of failures during the operation period *WDj*(*i*) is the deficit in the month *j* of the failure *WDj*(*i*) is the deficit in the month *j* of the failure *i.*

Using Rel, Res, and Vul, the last column of the SRI (shortage risk index) is shown. SRI is calculated as follows:

$$SRI = \frac{1}{3}Rel + \frac{1}{6}Res(med) + \frac{1}{6}Res(ext) + \frac{1}{6}Vul(med) + \frac{1}{6}Vul(ext) \quad (7)$$

Lower SRI index values correspond to a lower shortage risk assessment. The higher the SRI factor the greater the chance that there will be a risk of shortage.

In this case, SRI is around 0.25 which represents all the sum of RRV indexes.

The lower right panel showed in the Figure 6-8c represents inter-element flux, considering all elements connected to the selected resource. The left side of the graph shows the resources, in this example Wells Acquabianca and Capadacqua di Foligno. On the right side of the graph users are shown, in this example Foligno and Spello.

The lower chart (Figure 6-8d) shows mass balance variables of the considered element in this case Wells Acquabianca and Capadacqua di Foligno in Mm^3 in time. Also, it shows long term availability of water, water demand and overexploitation.

6.2.3. Output of Wells Cantone

After selecting the “plot element diagnostic” icon, the user clicks on the element to be displayed, and selects an available run to generate the figure. In the Figure 6-9. Output of Wells Cantone plot element diagnostic are shown.

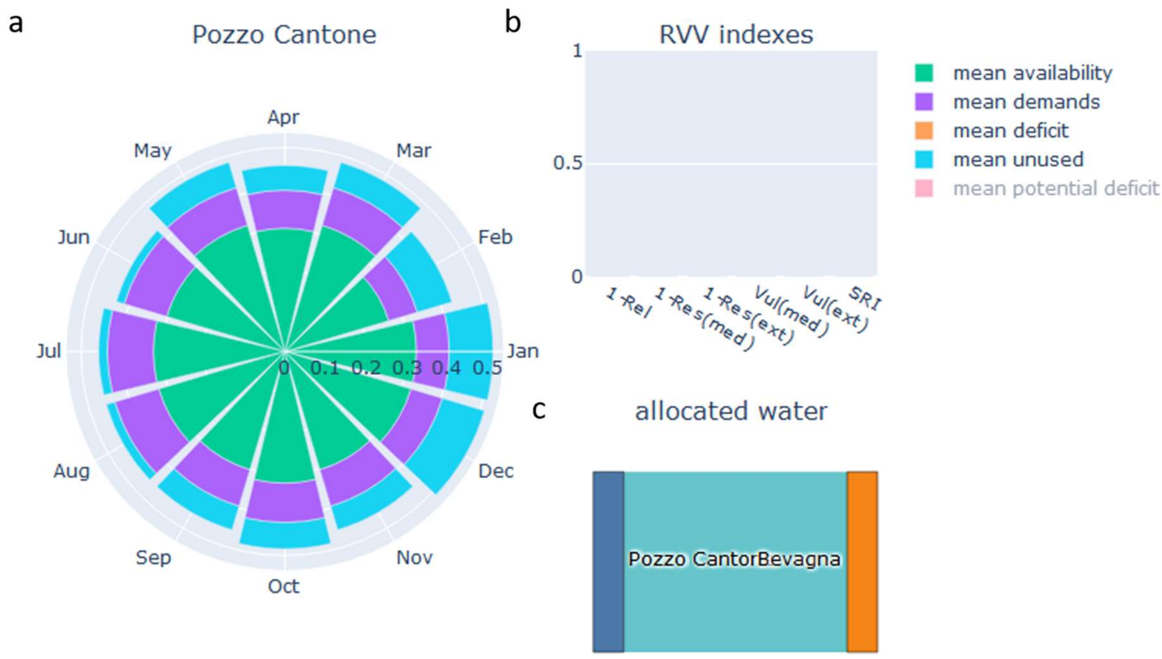


Figure 6- 9. Output of Wells Cantone. 6-9a shows monthly mean value of the considered element. 6-9b represents the RRV(Reliability-Resilience-Vulnerability) metrics. 6-9c shows inter-element flux, considering all elements connected to the selected resource

The panel of the figure 6-9a. is dedicated to the monthly value of the mass balance variables of the Wells Cantone in Mm³. The 6-9c panel shows inter-element flux, considering all elements connected to the selected resource. The left side of the panel 6-9c shows the resources, in this example Wells Cantone. On the right side of the 6-9c panel, user is shown, in this example town of Bevagna.

The table 6-2. shows the values of Wells Cantone input. Requirement of water needs for town of Bevagna can be quantifiable overall at about 42 l/s during summer season (June, July and August), 36 l/s during autumn season (September, October and November), 30 l/s during winter season (December, January and February) and 36 l/s during spring season (March, April and May). In our case, Wells Cantone has maximum withdrawals of 45 l/s which is constant throughout the year. The value of maximum withdrawals for Wells Cantone is higher than the demand of the town Bevagna. That's why it's on panel 6-9a. the value of the mean deficit cannot be observed. In this case, long-term availability is higher than long-term demand, so long-term overexploitation is zero. This can also be noticed in panel 6-9b. the SRI value is zero.

6.2.4. Output of Wells Vene del tempio

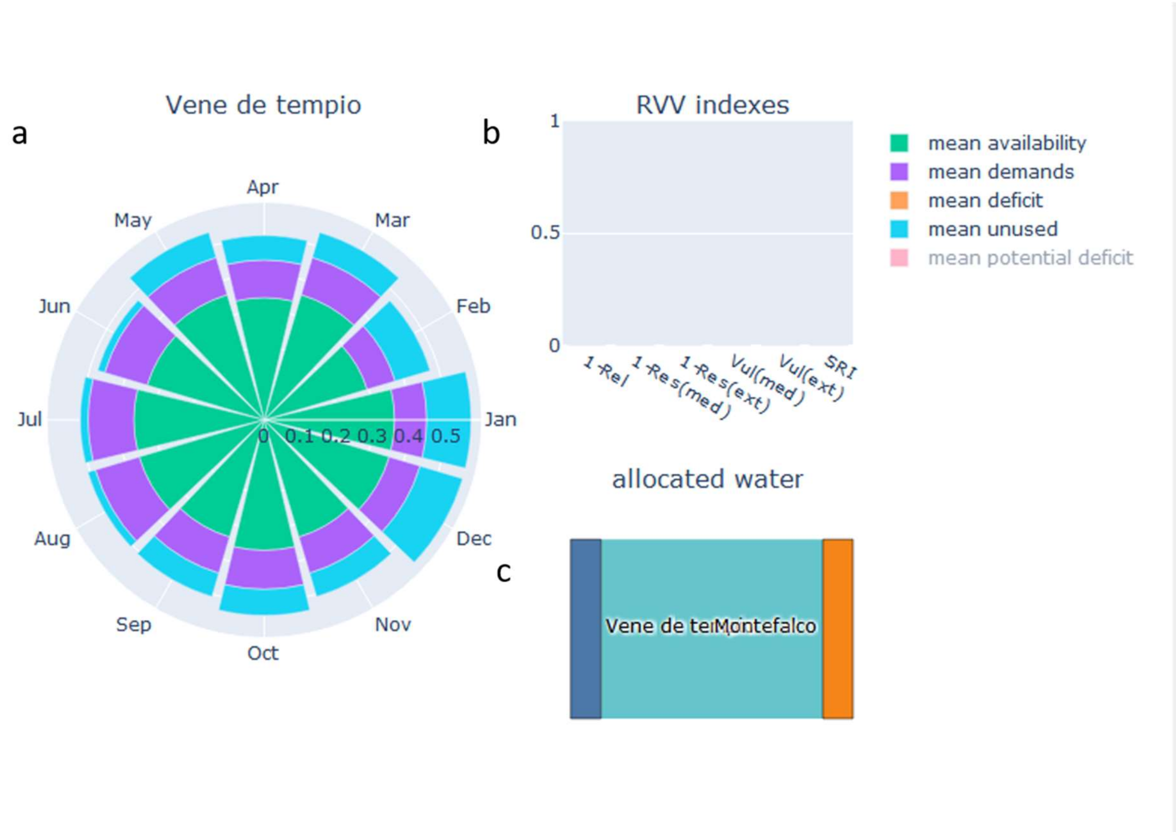


Figure 6- 10.. Output of Wells Vene del tempio. 6-10a shows monthly mean value of the considered element. 6-10b represents the RRV(Reliability-Resilience-Vulnerability) metrics. 6-10c shows inter-element flux, considering all elements connected to the selected resource.

The panel of the figure 6-10a. is dedicated to the monthly value of the mass balance variables of the Wells Vene del tempio in Mm^3. The 6-10c panel shows inter-element flux, considering all elements connected to the selected resource. The left side of the panel 6-10c shows the resources, in this example Wells Vene del tempio. On the right side of the 6-10c panel, user is shown, in this example town of Montefalco.

The table 6-2. shows the values of Wells Vene del tempio input. Requirement of water needs for town of Montefalco can be quantifiable overall at about 47 l/s during summer season (June, July and August), 40 l/s during autumn season (September, October and November), 33 l/s during winter season (December, January and February) and 47 l/s during spring season (March, April and May). In our case, Wells Vene del tempio has maximum withdrawals of 50 l/s which is constant throughout the year. The value of maximum withdrawals for Wells Vene del tempio is higher than the demand of the town Montefalco. That's why it's on panel 6-10a. the value of the mean deficit cannot be observed. In this case, long-term availability is higher than long-term demand, so long-term overexploitation is zero. This can also be noticed in panel 6-10b. the SRI value is zero.

6.2.5. Spring Rasiglia Alzabove early warning tool

In the figure 6-11. the output of Spring Rasiglia Alzabove warning tool is presented.

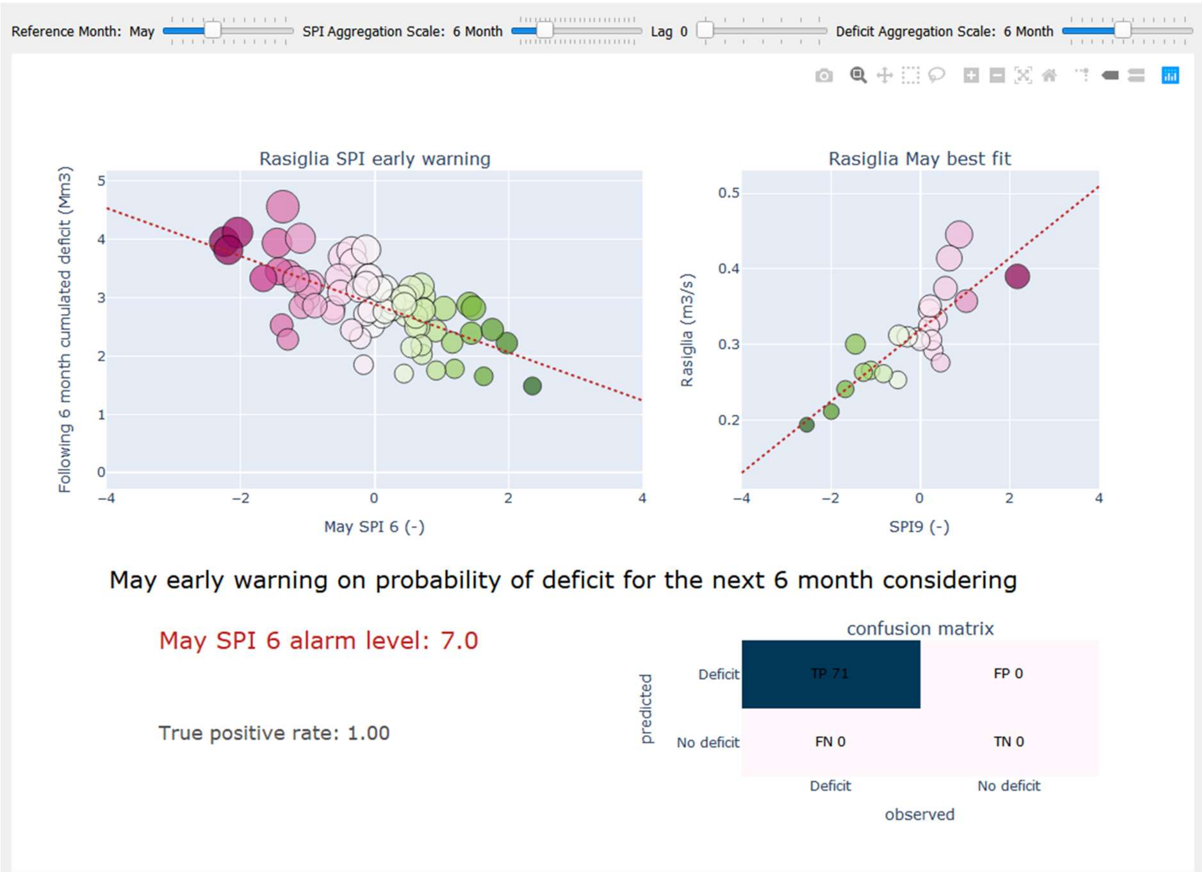


Figure 6- 11. Spring Rasiglia Alzabove early warning tool

When the "early warning" element is selected, the user then selects an available run to generate the figure for the considered SPRING. In this case, Spring Rasigli Alzabove.

In the upper menu, the user selects:

- The Reference Month. May is the selected reference month in this case;
- The SPI Aggregation Scale(previous precipitation). A 9 months reference period is selected in this case;

- The SPI lag(mean infiltration delay). A 0 month reference period is selected in this case;
- The Deficit Aggregation Scale(future deficit). A 6 months reference period is selected in this case.

Referent values are shosen randomly, just to show how support tool works.

A relationship is presented on the upper left panel between the SPI predictor (reference month precipitation anomaly, taking into account lag, cumulated on a selected aggregation scale, May SPI9) and the potential deficit during the next deficit aggregation scale months (next six months, August to January). Based on the hypothesis that the SPI predictor and future deficit are fairly linear, an SPI alarm level can be estimated as the point at which the linear regression of the non-null cumulated deficit intersects the SPI predictor.

During the calibration of the SPRING built-in model for the reference month, the best relation is displayed in the upper right panel.

On the left is a summary of the early warning demand and associated estimates of SPI and volume alarms, and the resulting early warning model is tested: a deficit is predicted when the selected SPI predictor value is less than the estimated SPI alarm. There are four categories for each month of the considered run:

- True Positive (TP) : a deficit has been predicted and actually occurred;
- False Positive (FP): a deficit has been predicted but does not actually occurred;
- True Negative (TN) : no deficit has been predicted and no deficit actually occurred;
- False Negative (FN) : no deficit has been predicted but a deficit actually occurred.

On the bottom right panel, the classification(TP, FP, TN, FN) is reported in the confusion matrix. As a final measure of early warning model performance, the following can be taken into account:

The True Positive Rate (TPR), defined as the ratio between the True Positive cases (TP) and the actual positive cases (TP+FN):

$$TPR = \frac{TP}{(TP+FN)} \tag{8}$$

The False Positive Rate (FPR), defined as the ratio between the False Positive cases (FP) and the actual negative cases (TN+FP):

$$TPR = \frac{FP}{(TN+ \quad)} \tag{9}$$

The TPR and FPR are both defined between 0 and 1. Generally, the more robust an early warning model is, the higher the True Positive Rate (->1) and the lower the False Positive Rate (->0). Lower left is a panel showing True Positive Rate and False Positive Rate.

Early warning support tool is shown on the Spring Rasiglia Alzabove. This chapter is dedicated to show how tool works. This element shows only the potential deficit of water supply system of city of Foligno, due to the distribution of priorities. As explained earlier, in the case of multi-resource-multi-user scheme, the actual deficit can be seen in the last element in the water supply system, i.e. in the element with lowest priority. In this case, actual deficit can be seen in the elment Wells Acquabianca and Capadacqua di Foligno.

7. DISCUSSION

For this Master's Thesis, the water supply system of the city of Foligno and its surroundings, which includes towns Spello, Bevagna, Trevi and Montefalco were created. Scheme is configured as a multi-resource-multi-user system. Scheme is implemented without any prioritization because the demand of water in this system is a demand of drinking water of five users. Requirement of water needs can be quantifiable overall at about 700 l/s during summer season (June, July and August), 600 l/s during autumn season (September, October and November), 500 l/s during winter season (December, January and February) and 600 l/s during spring season (March, April and May). Percentage distribution od of drinking water requirements are: Foligno 67.5%, Spello 9.8%, Bevagna 6.2%, Montefalco 6.7% and Trevi 9.8%. The demand of drinking water is satisfied by various types of resources: Wells Acquabianca and Capadacqua di Foligno, Wells San Pietro 1 e 2, Wells Vene del Tempio, Wells Cantone and Spring Rasiglia Alzabove. The wells elements are characterized with a maximum flow rate that can be extracted from wells element. Maximum flow rate that can be extracted from Wells Cantone is 45 l/s, from Wells San Pietro 1 e 2 is 70 l/s, from Wells Vene del tempio is 50 l/s and from Wells Acquabianca and Capadacqua di Foligno is 160 l/s. Spring Rasiglia Alzabove is characterized with a precipitation data measured from January 1951 to October 2021 and monthly inflow data measured from January 1998 to November 2021. The resources were created using SPRING and WELLS elements in INOPIA and users were created using USER elements, connected with CONNECTOR elements. The management rule has been implemented through the MANAGEMENT NODE element: each user element directs the drinking water requirement to the nearest local source (WELLS), then to the common Spring Rasiglia Alzabove and finally to the common Wells Acquabianca and Capadacqua di Foligno. The final scheme of the water supply system can be seen in the Figure 6-6.

After running the scheme, for each element the diagnostics is done. The output of Spring Rasiglia Alzabove is shown in the Figure 6-7., output of Wells Acquabianca and Capadacqua di Foligno is shown in the Figure 6-8., output of Wells Cantone is shown in the Figure 6-9., and output of Vene del tempio is shown in the Figure 6-10. Spring Rasiglia Alzabove early warning tool is shown in the Figure 6-11.

Water supply system satisfies the drinking water needs of the cities. It can be seen in the last element in the water supply system scheme which is Wells Acquabianca and Capadacqua di Foligno. The figure 6-8d shows the mass balance variables of the wells in Mm^3. On the lower panel of the figure, the events of overexploitation are shown. There are six events of overexploitation i.e., when demand is higher than availability of the resources.

The value of SRI factor of Wells Cantone, Wells Vene del tempio and Wells San Pietro 1 e 2 is zero. It means that these Wells are underused in the water supply system, while SRI for Wells and Acquabianca and Capodacqua di Foligno is approximately 0.25, and Wells Acquabianca and Capodacqua di Foligno is overused. Wells is overused due to the occurrence of overexploitation events since 1953. Lower SRI index values correspond to a lower shortage risk assessment. The higher the SRI factor the greater the chance that there will be a risk of shortage.

This is concluded based on the graph and size of the SRI factor, the higher the SRI factor the greater the chance that there will be a risk of shortage.

The actual deficit of the system can only be seen on the last resource on the priority list, in this case Wells Acquabianca and Capodacqua di Foligno. Currently, in the case of a multi-resource-multi-user scheme, the actual deficit (demand not met by the WSS) is registered according to resource elements equal to the potential deficit (demand is not addressed to a particular resource).

Except for the SRI value, prediction for a possible deficit can be taken from the output of early warning tool for Spring.

The tool Early warning support for Spring Rasiglia Alzabove is shown in the Figure 6-11. The tool, understood as the ability to predict a possible deficit, is based on: 1) the historical relationship between the standardized precipitation indicators and the associated reconstructed deficits. 2) the historical relationship between the volumes stored in a given month of the year and the reconstructed deficits.

The information necessary to support the early warning are: 1) the deficits estimated as unsatisfied needs; 2) the rainfall (one or more stations/nodes) used for the associated reconstruction; 3) the month considered; 4) the aggregation scale of the standardized precipitation indices (for example the precipitations of the last 6 months, represented by the SPI6); 6) the scale of aggregation of the expected deficits.

The results obtained for the water supply system of Foligno is made using the current version of INOPIA, while INOPIA is upgraded each day.

8. CONCLUSION

As part of this thesis, an informative support tool for the analysis of water scarcity risk in water supply systems consisting of more water resources connected to one or more water users was presented. The tool called INOPIA is implemented in QGIS computer software. INOPIA estimates robust indicators in line with EU standards, to support drought risk management and identify early warning indicators of water scarcity in water supply systems (Romano et al., 2018). With the help of such indicators, it is possible to react with appropriate measures to mitigate water shortages based on water-saving policies under EU standards. Using the data listed in Table 4.1. as input data of the water supply system model, monthly mass balance and statistical analysis of the time deficit of water are performed which can be seen in every element of the scheme excluding management node. The analysis yields self-calibrating multi-linear regression models (SPIQ model). Water deficits over the observed period are described by R-R-V metrics (Reliability-Resilience-Vulnerability), also including extreme deficit events which can be seen in every element of the scheme excluding management node. The results of the R-R-V metric are the indices user can use to implement specific measures to mitigate the consequences of the water crisis. In this thesis, the principle of INOPIA's work is presented using the example of the water supply system of the city of Foligno and its surroundings including towns Bevagna, Spello, Trevi and Montefalco. Shame is made using WELLS, SPRING, USER, CONNECTOR and MANAGEMENT NODE element. The aim of this thesis was to identify the “triggers” in order to implement a specific mitigation measures. These measures are based on water-saving policies on the example of Foligno water supply system scheme.

With the help of INOPIA, INOPIA’s user is improving the city's water scheme by allocating resources using management node to reduce pressure on water resources.

INOPIA is still evolving under agreement between Italian Presidency of the Council of the Ministry -Department of Civil Protection (DPC-Italian Civil Protection Department) and the Research Institute on Waters of the National Research Council Italy (IRSA-CNR) signed 9.1.2019., but with current capabilities, it can greatly facilitate solving water management problems around EU.

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