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Methodology for the assessment of groundwater resources sustainability: the case of the Lepini Mountains aquifer basin, Italy

Metodologia per la valutazione della sostenibilità delle risorse idriche sotterranee: il caso del bacino acquifero dei Monti Lepini, Italia

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Riassunto

L'effetto dei cambiamenti climatici sulla ricarica delle falde acquifere diventa sempre più importante e richiede un modello di gestione resiliente per un approvvigionamento idrico sicuro. È necessario adottare una visione più ampia del sistema e gli esseri umani devono diventare solo una parte del tutto. Il presente lavoro presenta una metodologia per valutare la sostenibilità delle risorse idriche in un bacino idrografico utilizzando un metodo semplificato del bilancio idrico. La metodologia utilizza i dati disponibili dalle stazioni meteorologiche e l'analisi storica delle temperature e delle precipitazioni nell'arco di 95 anni. I risultati ottenuti in un progetto precedente sono stati considerati per estendere i dati della stazione meteorologica di pianura all'intero bacino idrografico. I risultati presentano un buon accordo e ci consentono di condurre un'analisi preliminare dell'affidabilità del sistema idrico. La forte interconnessione tra deflusso e ricarica nell'acquifero dei Monti Lepini determina un tasso di fallimento dell'83%, in un contesto di portata media pari a 427 Mm^3/anno, indicando una situazione di criticità.. La gestione di questo sistema idrico dovrebbe essere condotta considerando tutti i servizi ecosistemici, non solo l'approvvigionamento idrico alle attività umane, ma anche gli ecosistemi acquatici esistenti presenti a valle dei sistemi sorgivi.

Abstract

The effect of climate change on groundwater recharge is becoming increasingly important and requires a resilient management model for a safe water supply. A larger view of the system must be adopted, and humans must become only a part of the whole. This work presents a methodology to evaluate the sustainability of water resources in a watershed using a simplified water balance method. The methodology uses available data from weather stations and the historical analysis of temperatures and precipitations over 95 years. The results obtained in a previous project were considered to extend the plain weather station data over the entire watershed. Results present a good agreement and allow us to conduct a preliminary analysis of the water system's reliability. The Mt. Lepini aquifer appears in a critical situation where the discharge is directly connected to the recharge with a failure rate of 83%, considering the average mean discharge of 427 Mm^3/y*. The management of this water system should be conducted considering all the ecosystem services, not only the water supply to human activities but also the existing water ecosystems present downstream to the spring systems.*

Introduction

The planet has been experiencing climate change for a few decades now, with a significant increase in global mean air temperature, sea surface temperature, rising sea levels, and impacts on the soil and land cover (D'Agostino et al., 2014; Hamed et al., 2018).

The consequences of climate change on water are noticeable everywhere globally, especially in zones prone to droughts. As seen in the northern part of the African continent, groundwater is the only source of water in those arid lands (Mapani et al., 2023). Considering that the water crisis affects agriculture and socioeconomic activities is essential. In addition, the cities welcome an ever-growing population, leading to an over-exploitation of water resources (Mapani et al., 2023).

It is essential to introduce sustainable water management practices to ensure the ability to meet the present water demand for future generations. It requires a multidisciplinary and holistic approach addressing technical, environmental, economic, societal and cultural issues. The United Nations General Assembly recognized "the right to safe and clean drinking water and sanitation as a human right essential for the full enjoyment of life and all human rights".

Thus, the impact of climatic change on groundwater recharge is becoming essential, and to ensure a safe water supply, a resilient management model for water resources is required. This trend toward a resilient management model for water resources includes several United Nations Sustainable Development Goals (UN, 2022). Those goals call us to change a drastic paradigm for a new era. It is crucial to introduce management and adaptation strategies to ensure the long-term sustainability of groundwater to be resilient. Learning from the experience of other regions and countries can be immensely useful, but caution is required in transferring management strategies from one set of circumstances to another (Shah, 2014).

Cities, governments, and people worldwide must cope with climate and water crises. Thus, they are implementing solutions to manage the crisis and adapt to new climate conditions. Each country needs to develop an integrated groundwater governance system tailored to its unique social, ecological, economic, and political conditions. There is no one-size-fits-all approach to organizing and managing a country's groundwater, as the combinations of resources, people, society, economy, and politics vary significantly across different places and periods. Successfully implementing a policy goal depends on a complex interplay of social, economic, and political factors.

Agriculture has become vulnerable. In many rural zones, agriculture is the primary source of income for the people living there, but sadly, making a living out of it is hard today (Goma et al., 2021). Water stress and groundwater depletion affect "agricultural and industrial activities as well as food security" (Mianabadi et al., 2023). Farmers are forced to abandon their lands to live in the cities.

Meteorological droughts always affect many people with adverse impacts such as crop-yield failure, erosion of soils, unemployment, lowered incomes, malnutrition, and even psychological problems. Thus, meteorological droughts can become socioeconomic problems (Magana et al., 2021).

For optimal management, sustainability cannot be forgotten. The projects, ideas, and plans must be sustainable, long-lasting, and efficient. For instance, it is necessary to wonder if groundwater resources are sustainable (Blak et al., 2023). Groundwater abstraction could affect groundwater quality and quantity and would not be a long-term viable solution.

Sustainability is complex; it implies sustainability at each level and sector. Sustainable governance means anticipation, more participation and cohesion. Sustainability is the key to good management plans and policies (Khouri, 2003).

Given the seriousness of the current water crisis, management must be sustainable and need to include both people on a small scale and governors and experts on a larger scale. In the last decades, the primary management actions have been groundwater abstraction, desalination, and recycling of used water.

Considering weather and climate data forecasts, it is possible to consult different maps created by IPCC WGI Interactive Atlas (IPCC 2024) and Copernicus (Copernicus, 2024). Future projections can be analyzed in the Interactive Atlas using periods (short, medium, and long term: 2021-2040, 2041-2060 and 2081-2100, respectively) and levels of global warming (1,5°C; 2°C; 3°C and 4°C). Through these simulations, it is possible to observe how variations in precipitation and temperature are expected for the three periods, compared to a reference period 1971-2000. Going to observe in the area, what is expected is an increase in temperature between 0.5 and 1.25 °C and a change in precipitation between -5% and 10%, especially in the case of temperatures, which show a trend towards higher and lower maximum temperatures and lower minimum temperatures.

These conditions and the need for a fast-forecasting method have guided this work to build a simplified model to evaluate and manage the groundwater of a specific area in central Italy near Rome. Why simplified models? The answer comes from the experience of developing and using a distributed water balance model. The amount of information and data required is so large that it becomes difficult to maintain a complete data set over a long time. The second aspect regards old data analysis, whose availability does not cover all the parameters and total coverage, especially in mountain areas. A recent review on how climate change affects groundwater recharge gives a clear view of modelling approaches. The results show that process-based modelling is the most adopted approach due to its accuracy and detailed results. Instead, a simple water balance is selected due to lower data requirements (Al Atawneh et al., 2021). From this consideration, a lumped parameter model is chosen to build a fast predictive model based on the meteorological conditions. This model will allow us to verify the resilience of the aquifer to climate change and to have the possibility to give warnings and alarms.

In 2004, a research project under the patronage of the Roffredo Caetani Foundation was founded by the Lazio region and conducted for five years. The main result of the "Tutela delle risorse idriche dei Monti Lepini" project was a new, updated geological and hydrogeological model and mapping of vulnerability and pressure over the system (AA. VV., 2011). The experience matured across this five-year project and gives us some indications for approaching possible water management. This work wants to be an extension of the previous project to develop a simplified model to analyze the evolution of the M. Lepini aquifer. The collected data during the "Tutela delle risorse idriche dei Monti Lepini" project have been used to revise some assumptions and use them for calibration purposes of the simplified model.

Materials and Methods

Study area and data collection

Several researchers studied the area of Mt. Lepini considered in this work. Celico (1983) studied the hydrogeology of the carbonate complex in central-southern Italy. He built a circulation model and synthesized the primary data on the spring system and the hydrodynamic measurements. In 1986 (Boni et al., 1986), the hydrogeological scheme of central Italy, including the Mt. Lepini system, was improved.

Geological and Hydrogeological Setting

The Lepini, Ausoni, and Aurunci mountains form the pre-appenninic Volsci range (southern Lazio). The Mt. Lepini ridge extends in the NW-SE direction for about 20 km, and its width ranges from 25 to 30 km and its height from 1000 m to 1536 m of Monte Semprevisa (Cosentino et al., 2009). The ridge, made of a series of stratified carbonate rocks (limestones, dolomitic limestone and dolostones) mainly from the Mesozoic era, is cut into large monoclines dislocated at different depths with mainly NE-dipping (Parotto et al., 2013).

The hydrogeological system of Mt. Lepini consists essentially of deposits belonging to the hydrogeological complex of the carbonate platform. The prevailing formations are represented by limestones and dolomitic limestones, which are highly permeable due to fracturing and karstification. To the northeast, the limit is constituted by the thrust front of the Lepini massif on the low permeability deposits of the Latina valley (Fig. 1).

There are three main complexes: the limestone complex, the volcanic and travertine deposits complex, and the Pontine plain clayey-sandy deposits complex. The limestone complex is characterized by fractured and karstified Mesozoic limestones in the emerged part (Lepini mountain ridge) and the lowered part (submerged under the Plio-Quaternary deposits of the

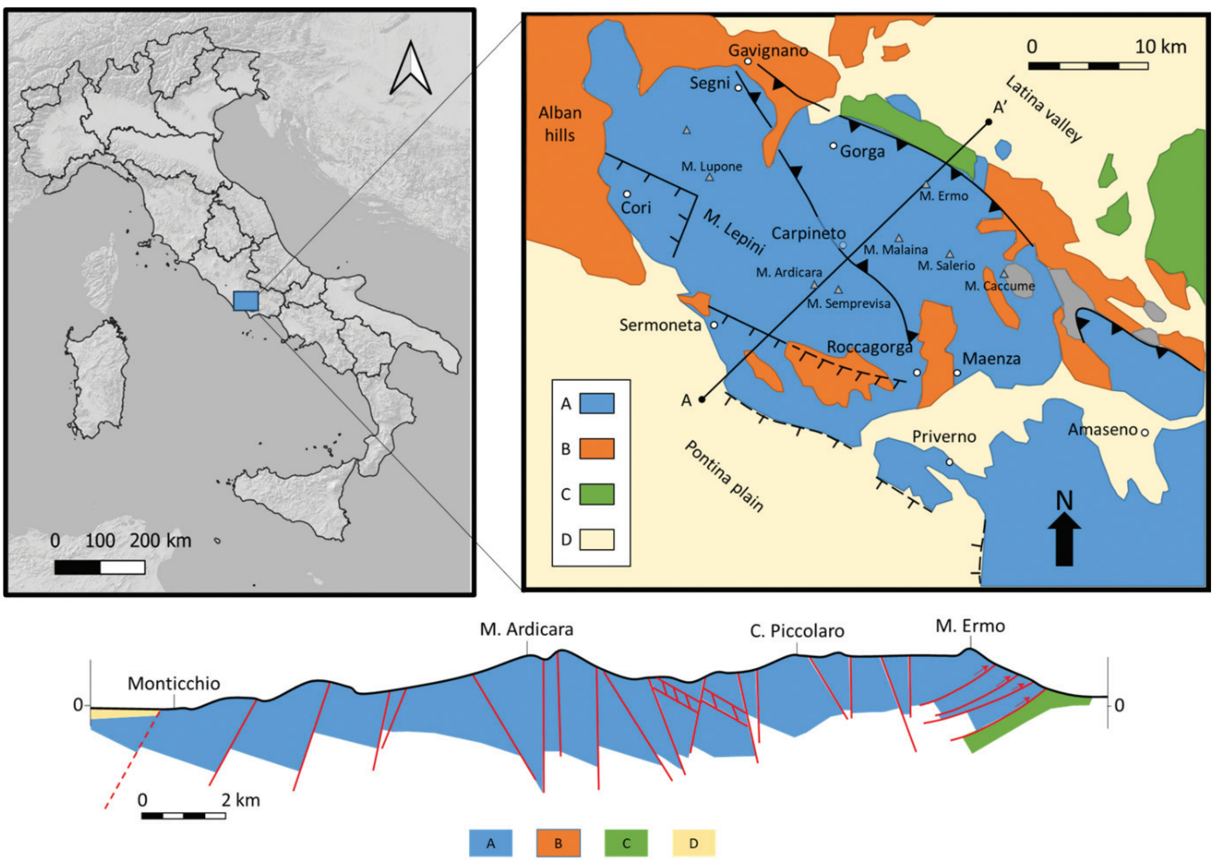

Fig. 1 - Location and geology of the study area: A Limestones, dolomitic limestones and dolomites; B Lavas and pyroclastic deposits; C Clays, sandstones, marls and marly limestones; D Alluvial and detrital deposits.

Fig. 1 - Ubicazione e geologia dell'area di studio: A Calcari, calcari dolomitici e dolomie; B Lave e depositi piroclastici; C Argille, arenarie, marmi e calcari marnosi; D Depositi alluvionali e detritici.

Pontine plain). This complex hosts the phreatic carbonate aquifer within the emerged ridge and the pressure aquifer in the buried area confined by the marine deposits of the Upper Pliocene - Middle Pleistocene (Teoli, 2012).

Along the south-western border, Mt. Lepini, lowered by direct faults, is in contact with the Quaternary soils of the Pontina plain, which constitute a partially watertight limit as it, in any case, allows a limited flow into the aquifer of the plain itself.

From a hydrogeological point of view, two reservoirs can be considered (Capelli et al., 2011). The main reservoir is Mt. Lepini, which represents the recharge system of the aquifer. The second reservoir is buried in the Pontina plain. These reservoirs are carbonate deposits underlying volcanic or alluvial deposits confining the basal limestone aquifer. Hydraulic connection between the two aquifers occurs at the base of the limestone massif, where several important overflow karst springs discharge a large quantity of water. Figure 1 shows the geo-structural configuration of the Mt. Lepini unit acquired from the upper Miocene to the late Quaternary. The consequent scheme of the groundwater circulation is reported in Figure 2.

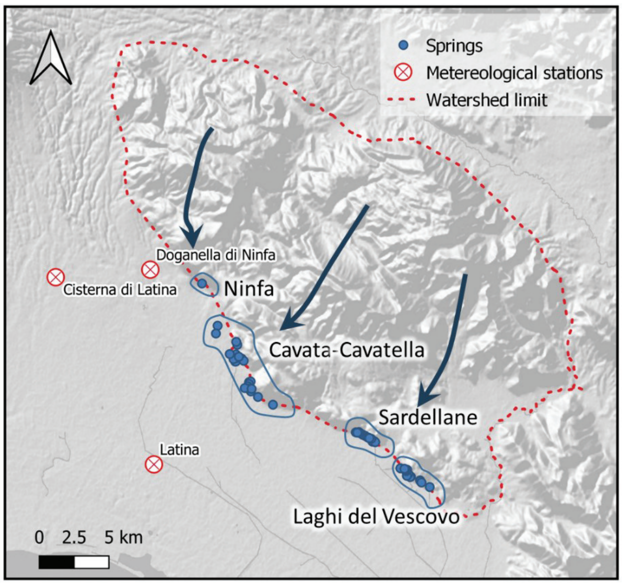

Fig. 2 - Weather stations used in the study, and hydrogeological flow and spring groups.

Fig. 2 - Stazioni meteorologiche usate nello studio, schema di flusso idrogeologico e gruppi sorgivi.

Climate data and analysis

Defining the climatic data expressed by rainfalls and temperatures is essential to describe the study area. Those data are required in the simple water balance model.

The statistical analysis of rainfall and temperature allows for defining the probability distribution function for the two main variables needed to evaluate recharge volume. The data on rainfall and temperature available on local weather stations on a monthly scale were collected mainly from the Cisterna di Latina, Latina and Doganella di Ninfa stations, as presented in Figure 2. Following the data availability, the data sources are the web services of Servizio Integrato Agrometeorologico della Regione Lazio (https://siarl.arsial.it/) and Servizio Idrografico Regione Lazio (https://protezionecivile.regione.lazio.it/gestione-emergenze/centro-funzionale/servizio-idrografico).

The available data is from 1921 to 2020. Across this time, the plain below Mt. Lepini was highly modified. Between 1932 and 1934, the Bonifica Integrale Pontina, a significant reclamation project of wetlands, was realized, including hydraulic and sanitary remediations. Littoria was founded in the middle of the reclaimed area in 1936 and was recently renamed Latina. This deep change produced a considerable change in the territory, increasing the population from a few thousand people to hundreds of thousands today. In the meantime, the land use changed from prairies to agricultural and, more recently, industrial uses. Table 1 reports the primary statistical analysis parameters on yearly rainfall and temperature.

Tab. 1 - Annual rainfall (mm) and temperature (°C) statistics (1921-2018).

Tab. 1 - Statistica delle precipitazioni (mm) e temperature (°C) annuali (1921-2018).

	Annual rainfall	Annual temperature
Mean	961	16.1
Standard Deviation	233	0.7
Maximum	1649	17.2
Minimum	477	13.2

The trend analysis highlights a smooth increase in the average rainfall, but the most critical aspect is the change in the behaviour that seems more spread. Figure 3 shows the rainfall trend and its histogram. The probability distribution is a lognormal one, as also shown by the histogram plot.

The analysis of the pre- and post-1990 trends in rainfall highlights a fascinating aspect. From 1921 up to 1990, the trend in rainfall is substantially constant with a slight decrease. The annual mean value is 946 mm with a standard deviation of 199 mm. The period before 1940 presents an annual mean value of 1016 mm with a standard deviation of 144 mm. Instead, the period 1990-2020 analysis shows an annual mean value of 1010 mm with a standard deviation of 291 mm. The trend is growing. The annual mean values are similar, but the standard deviation is more significant, indicating a more considerable fluctuation increase between low and high rainfall years.

The average annual temperature shows a growth trend of 0.7 °C in a century, and the temperature values fit a normal distribution (Fig. 4). The trend analysis highlights a rapid increase in temperature in the last 20 years, with an increase in the maximum temperature and a decrease in the minimum one. Considering 1924-1990, the average temperature is 16.0 °C with a smooth increase. Instead, between 1990 and 2020, the average temperature is 16.6 °C. A similar trend has been observed in Algeria with a temperature increase of 1.8 °C (Kherbache et al. 2023) and Central France with a gradient of +0.05 °C/y (Labbe et al., 2023).

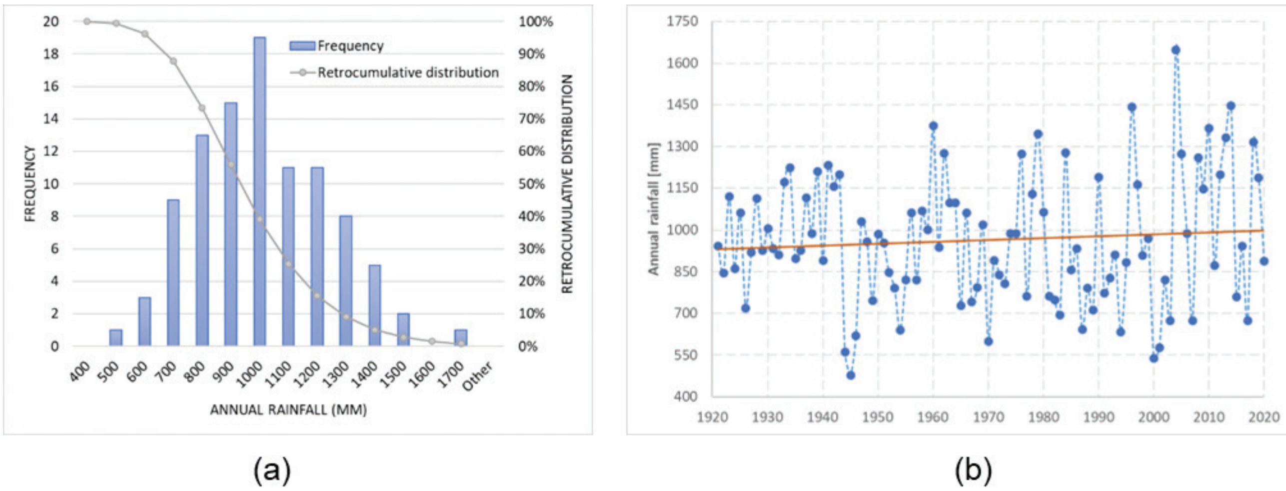

Fig. 3 - Annual rainfall (1921-2020). (a) Trend and (b) frequency histogram and retrocumulative distribution.

Fig. 3 - Precipitazione annuale (1921-2020), (a) andamento e (b) istogramma della frequenza e distribuzione retrocumulata.

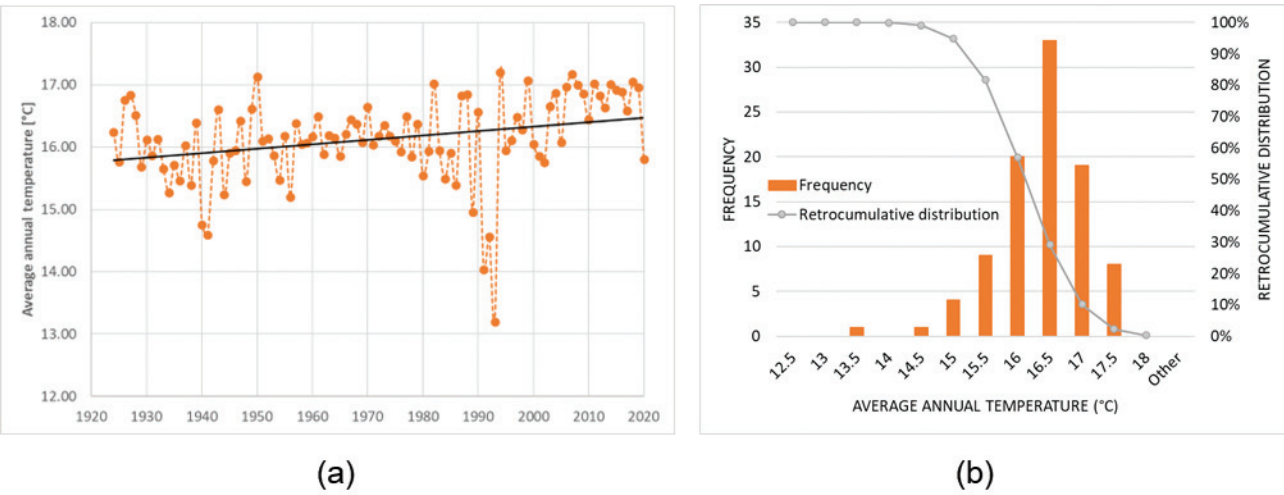

Fig. 4 - Average annual temperature (1924-2020). (a) Trend and (b) frequency histogram and retrocumulative distribution.

Fig. 4 - Temperatura media annuale (1924-2020), (a) andamento e (b) istogramma di frequenza e distribuzione retrocumulata.

Base flow

The Mt. Lepini hydrostructure base flow comes from the basal springs concentrated in the foothill line on the southeast side (Fig. 2). There are four main springs: the Ninfa Spring in the northern part, the Cavata/Cavatella spring group, the Sardellane springs and the Laghi del Vescovo springs. During the "Progetto Monti Lepini" (Capelli et al., 2011), the flow rate of each spring was measured. From the measured flow rate, the average discharge in 2000-2008 was 10.4 m^3/s. Table 2 also reports discharge base flow from previous works (Mouton, 1977; Celico, 1983; Boni et al., 1986).

Comparing the measured data from 2000 to 2008 with the previous works, a decline in the discharge of about 5 m^3/s appears in 15 years. During this time, the human pressure on water resources increased due to the growth of the industrial sector (mainly pharmaceutical) and the evolution of crops, moving from low water demand to high water demand crops, like Actinidia (commonly called kiwi). Groundwater irrigates crops in the northern part of the plain, while irrigation systems are used in the southern plain. Concerning withdrawals for domestic use, the population growth from the 1970s is essential. The population has almost doubled, thus increasing the anthropogenic pressure on the water system (Rizzoli, 2024).

Tab. 2 - Baseflow discharge (m^3/s) from the Mt. Lepini structure.

Tab. 2 - Portate (m^3/s) basali dei Monti Lepini.

Year	Baseflow
2000	10.46
2003	8.9
2004	11.26
2005	12.3
2007-2008	9.55
Previous works	
1977	14.8
1983	14.9
1986	15.0

Aquifer recharge

On a territory so variegated either orographically or hydrographically, a careful analysis of the different aspects of the water balance is necessary. The recharge volume of the aquifer is obtained by modelling the water cycle phenomena. Previous works (Mazza et al., 2014) highlighted the importance of calculating the water balance on a hydrogeological basin in a distributed form to consider the spatially variable soil characteristics and the rainfall and temperature, which are variable in space and time. Following the methodology described in Alimonti et al. (2011) and resumed by Mazza et al. (2014), the aquifer recharge over six years (2005-2010) has been evaluated considering a hydrological balance for the study area with a specific procedure. This procedure was based on a distributed parameter approach which considers the physical characteristics of the aquifers, determining the recharge, anthropic effects on hydrology and hydrogeology due to withdrawals and human-induced alterations to watercourses, variation of the boundaries of the catchment during time due to variation of the recharge or the withdrawal amount. The recharge area is 657 km^2 wide, and the altitude varies from 10 to 1450 metres (orthometric height) with an average altitude of 612 m. In Table 3, the calculated volumes of water recharge are reported. Between 2006 and 2007, the water recharge was strongly reduced to less than half of the recharge obtained in the rest of the period. The coefficient of variation, defined as the standard deviation divided by the mean of the annual inflows, is equal to 0.31.

Tab. 3 - Water recharge (m^3/s) of Mt. Lepini aquifer (AA.VV, 2011).

Tab. 3 - Ricarica idrica (m^3/s) dagli acquiferi dei Monti Lepin (AA.VV, 2011).

Year	Recharge
2005	15.8
2006	8.9
2007	6.3
2008	14.6
2009	13.8
2010	15.6

Compared with the base flow measurement, it is not always possible due to the lack of measures over the last six years. In 2005, the base flow was 12.3 m^3/s, showing a positive balance for the recharge of 15.8 m^3/s. In the biennial 2007-2008, the average recharge (10.45 m^3/s) was more significant than the base flow (9.55 m^3/s Table 2). These differences do not consider the shift in time of the recharge that generally occurs between October and March. The calculations are done over the solar year and not on the groundwater cycle.

Water balance model

The water balance can be a valuable tool in analyzing groundwater resources. In literature, several authors confirm the fundamental role of the water balance in water management strategies, including the water supply infrastructure and the water needs of ecosystems (Mays, 2013; Healy et al., 2007; Konikow, 2011).

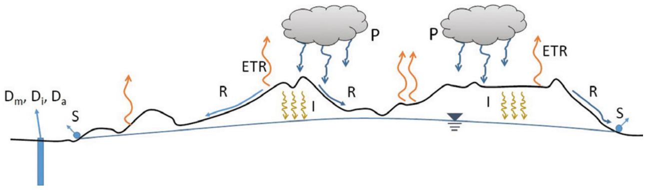

Fig. 5 - Water balance model scheme. P – rainfall; R – runoff; ETR – actual evapotranspiration; S – spring; I – infiltration; D_m - domestic water demand; D_i - industrial water demand; D_a - agricultural water demand.

Fig. 5 - Schema del modello di bilancio idrico. P- precipitazione; R - ruscellamento; ETR - evapotraspirazione attuale; S - sorgente; I - infiltrazione; Dm - domanda idrica uso domestico; Di - domanda idrica uso industriale; Da - domanda idrica uso agricolo.

The water balance model is based on a simple and global balance model instead of a distributed one. A simple and fast method allows analysis, including periods where climate-distributed data are unavailable. Two different water budgets are present (Fig. 5); the first is the hydrologic one:

$$P - ETR = PE = R + I \qquad (1)$$

where P is the rainfall, ETR is the actual evapotranspiration, PE is the effective rainfall, R is the runoff, and I is the infiltration that accounts for the aquifer recharge.

The second one concerns the aquifer water budget, and it is the following:

$$I = S + Q_d + Q_a + Q_i + \Delta V_{GW} \qquad (2)$$

where I is the infiltration, S is the springs flow, Q_d is the domestic withdrawal, Q_a is the agricultural withdrawal, Q_i is the industrial withdrawal, and ΔV_{GW} is the change in groundwater storage.

The recharge of the aquifer is estimated using a direct method with an infiltration coefficient named CIP (Potential Infiltration Coefficient), applied to the net rainfall,

$$I = (P - ETR) \cdot CIP \qquad (3)$$

The actual evapotranspiration (ETR) must be calculated to obtain effective rainfall. To maintain a simplified approach and using only rainfall and temperature as independent data, the Turc model (Turc, 1955) is selected,

$$ETR = \frac{P}{\sqrt{0.9 + \left(\frac{P}{L}\right)^2}} \quad L = 300 + (25 \cdot T) + 0.05 \cdot T^3 \qquad (4)$$

where P is the yearly rainfall in mm, and T is the average yearly temperature in °C.

The factors that contribute to determining infiltration are multiple, such as the spatial and temporal distribution of precipitation, the morphometric parameters of the survey, the distribution of ground temperatures, the hydrogeological and stratigraphic characteristics of the outcropping formations, and land use. Significantly non-linear behaviours characterize the dynamics between these parameters; their modelling inevitably requires a degree of high approximation (Brugioni et al., 2008).

The CIP is generally related to the lithological nature of the coverage. In this approach, the CIP is formed by two-component: CIP_g related to the geological outcropping formation, and CIP_{ps} considering the slope and the land use,

$$CIP = CIP_g \cdot CIP_{ps} \qquad (5)$$

The CIP_g is obtained from the values available in the literature concerning geological formations (Celico, 1988). Considering the geological formation distribution, the average value of 75.8% is assigned (Table 4).

Tab. 4 - Calculation of the geological potential infiltration coefficient CIP_g.

Tab. 4 - Calcolo del coefficiente di infiltrazione potenziale CIP_g.

Lithology	Coverage	CIP_g
Dolo-Limestones	85.0%	80.2%
Gravel, sand, clay, silt	15.0%	50.9%
Total	100%	75.8%

The tables shown in Figure 6 were used to estimate the CIP_{ps} value, where four quality classes are identified (from E - high, up to B - low). The definition of each class comes from scores assigned based on the slope and land use in the area under study (Brugioni et al., 2008).

Figure 7 shows the distribution of the three parameters used to estimate the CIP_g and the CIP_{ps}. The slope is obtained with the default algorithm in QGIS using the digital elevation model with an accuracy of 10x10 metres. The average slope is around 19% and corresponds to class 4. The predominant land use is "Cultivated land", which corresponds to 50.7% of the total area. The corresponding class is 30. Entering the table in Figure 6, the matching class for the CIP_{ps} is M, with a value of 65%. Then, the final CIP value is 49.3%.

Fig. 6 - Tables for CIP_{ps} estimation (modified from Brugioni et al., 2008)

Fig. 6 - Tabelle per la stima del CIP_{ps} (modificato da Brugioni et al., 2008)

Slope class	Description
1	0-3%
2	3-10%
3	10-15%
4	≥ 15%

Land use class	Description
10	Urban area
20	Pastures
30	Cultivated land
40	Forest

CIP_{ps} class	Value
B	50%
M	65%
A	85%
E	100%

		Land use			
		10	20	30	40
Slope	1	B	A	E	E
	2	B	M	A	E
	3	B	M	M	A
	4	B	B	M	A

Sustainability indexes

Performance indicators are typically used to characterize stochastic performance metrics of water resources systems (Mays, 2013; Sandoval et al., 2011). They can be applied to groundwater systems, defining their reliability, resilience, and vulnerability. The reliability index is defined as follows:

$$REL = \frac{\#\ of\ satisfatory\ condition}{total\ \#\ conditions} \qquad (6)$$

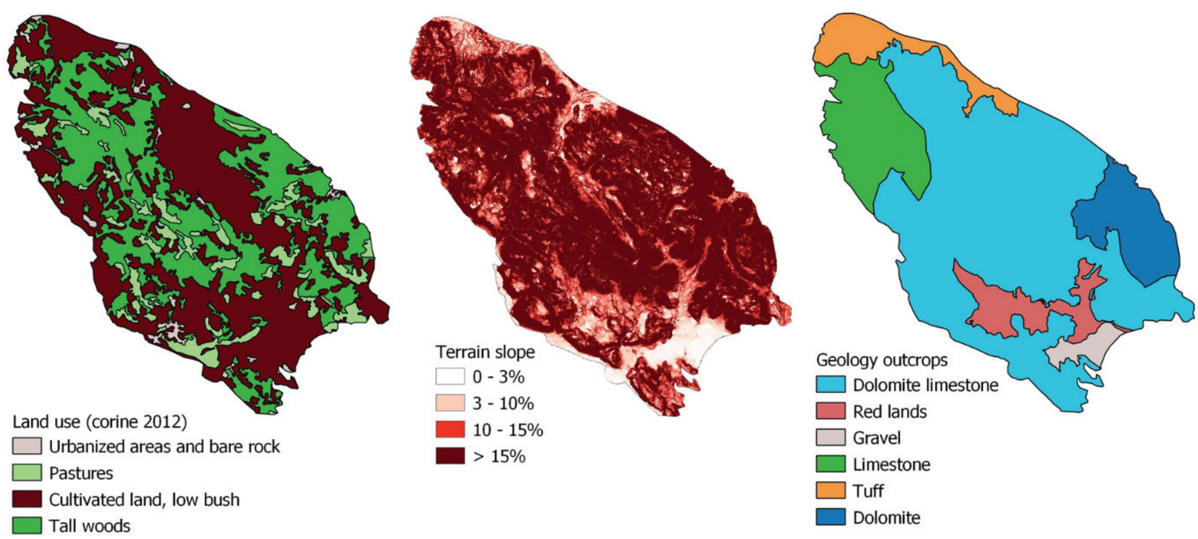

Fig. 7 - Distribution map of the three parameters used in potential infiltration coefficient estimation. a) Land use (Corine, 2020); b) Terrain slope; c) Geology outcrop.

Fig. 7 - Mappa della distribuzione dei tre parametri usati nella stima de coefficiente di infiltrazione potenziale a) Uso del suolo (Corine, 2020) b) inclinazione del terreno c) formazioni affioranti.

This performance index is the probability that no failure occurs within a period (Hashimoto et al., 1982). The resilience index is defined as:

$$RES = \frac{\#\ times\ satisfatory\ condition\ follows\ factory}{total\ \#\ unsatisfactory\ conditions} \tag{7}$$

Resilience represents how fast a system returns to a satisfactory condition after an unsatisfactory condition. The vulnerability index is defined as:

$$VUL = \frac{\#\ of\ \ unsatisfatory\ conditions}{total\ \#\ \ conditions} \tag{8}$$

Vulnerability is the probability that an unsatisfactory condition can occur without considering how long the failure persists.

The sustainability index is defined as the combination of the three performance indexes as follows:

$$SI = \sqrt[3]{REL \cdot RES \cdot (1 - VUL)} \tag{9}$$

Water demand and withdrawal data

The relationship between supply and demand has been analyzed following the primary indication in Alimonti et al. (2011). The study of water withdrawals identifies the domestic, industrial, and agricultural uses. Each use has been carried out as a collection of available data on withdrawal or an estimate when no data were available. An estimate of the water demand for single use has been conducted.

Based on the available data, the yearly domestic water demand is around 1.17 m^3/s. Between 2006 and 2008, public captions produced and distributed 1.37 m^3/s of water. The estimated withdrawal by private wells is evaluated at about 0.07 m^3/s per year (see Table 5).

Tab. 5 - Annual domestic demand (m^3/s) and withdrawal (m^3/s) from Mt. Lepini Aquifer.
Tab. 5 - Richiesta idrica per usi domestici e prelievi dai Monti Lepini.

	Domestic
Demand	1.17
Withdrawals	
Public wells	1.37
Private wells	0.07
Total	1.44

The industrial sector requirements were evaluated using three data sources (ISTAT data, Permits and wastewater discharge), summarised in Table 6. An average flow rate of 0.954 m^3/s is assumed.

Tab. 6 - Water demand (m^3/s) of industrial activities.
Tab. 6 - Domanda idrica (m^3/s) per usi industriali.

Uses	ISTAT	Permits	Wastewater
Production	0.661	0.667	1.052
Sanitation	-	0.089	-
Firefight	-	0.319	-
Irrigation	-	0.075	-
Total	0.661	1.150	1.052

The water supply consists of superficial water and groundwater. The Consorzio di Bonifica dell'Agro Pontino (CBAP) supplies the southern part of the Pontina plain, which is committed to giving and managing water for irrigation. Its waterworks determine the water distribution. Only a part of the withdrawal is by wells. The northern plain shows more withdrawals from wells because only a tiny part is serviced by the CBAP. Most of the wells get water from Mt. Albani and Mt. Lepini waters.

On the other hand, the southern plain uses just water from Mt. Lepini. Compared to the volume drained from the massif, the volume withdrawn from the springs is about 12%. Table 7 contains the synthesis of the water collection for agricultural use.

Tab. 7 - Water withdrawal (m^3/s) of agricultural activities.
Tab. 7 - Prelievi idrici (m^3/s) delle attività agricole.

Withdrawal		**(A+B) %**
CBAP Irrigation plants	0.410	27.9 %
CBAP Derivations	0.330	22.6 %
Sub-total (A)	0.740	50.5 %
Wells Southern Area	0.560	38.1 %
Wells Northern Area	0.170	11.4 %
Sub-total (B)	0.730	49.5 %
Total (A+B)	1.47	100 %

The water deficit estimated for agriculture on the plain area is about 1.47 m^3/s per year, of which 60% is in the southern area and 40% in the northern ones. The reduction of the volume of water withdrawn by wells leads to a total volume from the Mt. Lepini system of around 1.3 m^3/s per year.

Results and Discussion

Firstly, the global water balance on Mt. Lepini aquifer is finalized. The withdrawals for each category and the spring outcomes are summarised as total discharge. In the meantime, the recharge of the groundwater based on the infiltration is reported. Table 8 presents the study's outcomes.

Comparing the total discharge D to the water recharge R of Mt. Lepini aquifer over six years (2005-2010), the system is nearly balanced, slightly underbalanced (7.5%). The most important aspect is the base flow, which constitutes 77% of the total discharge. The base flow is strictly related to the ecosystem services and the environmental sustainability of the biosphere.

The quality status of internal surface waters refers to the Water Framework Directive 2000/60/EC (ARPA Lazio, 2021), transposed with Legislative Decree 152/06, which has deeply innovated the quality objectives and procedures of investigation and evaluation. In general, all regulatory provisions are intended to ensure, including through sector planning, the preservation of the resource and the rehabilitation of the water heritage from pollution and, at the same time, to prevent the depletion of resources in quantitative terms (Lazio Innova, 2021).

Tab. 8 - Water balance (m^3/s) and summary of withdrawals (m^3/s) by use (2005-2010).
Tab. 8 - Bilancio idrico (m^3/s) e somma dei prelievi (m^3/s) per campo d'impiego (2005-2010).

	Flowrate	%D
Measured base flow (BF)		
Agricultural (CBAP plants)	0.74	5.5%
Waterways	9.66	71.4%
Total (BF)	10.40	76.9%
Groundwater Withdrawals (GW)		
Domestic	1.44	10.7%
Industrial	0.95	7.0%
Agricultural	0.73	5.4%
Total (GW)	3.12	23.1%
Total discharge (D = BF+GW)	13.52	100%
Mean Recharge (R)	12.50	92.4%

Therefore, the first insight into the water budget of the Mt. Lepini aquifer was given. A water budget is an accounting of water stored within and exchanged among some subset of the compartments, such as a watershed, a lake, or an aquifer. A water-budget accounting unit may consist of a single part of one compartment, such as a lake, or an accounting unit may comprise parts of all three compartments, such as a watershed (Healy et al., 2007). Figure 8 provides a graphical representation of the water budget for the Mt. Lepini watershed.

The diagram in Figure 8 enables us to comprehend the flow of water volumes within a basin or irrigation system. It does so by categorizing water into four primary types:

1. Gross Inflow: Water entering the system.
2. Storage: Water retained within the system (positive) or released from storage (negative).
3. Depleted Water: Water lost from the system due to usage, evaporation, or withdrawal.
4. Reserved Outflow: Water directly discharged from the system for downstream use, which may or may not be utilized.

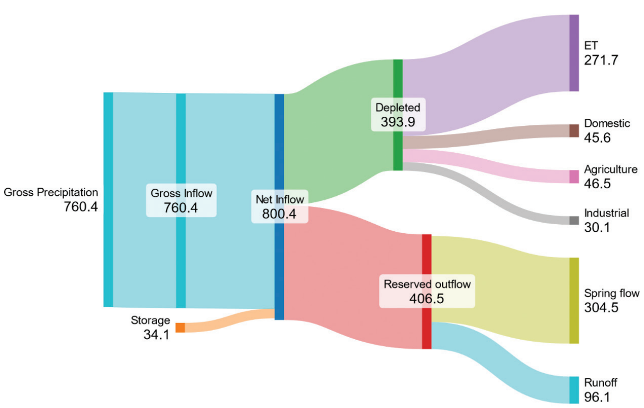

Fig. 8 - Diagram of the water budget of Mt. Lepini basin (Mm^3).
Fig. 8 - Diagramma del bilancio idrico del bacino dei Mt. Lepini (Mm^3).

The water budget of the Mt. Lepini watershed gives an image of the weak elements causing a water crisis. The main weakness is due to the severe impact that withdrawals can have. This weakness is related to the spring flow, which should be considered a reserved outflow supplying downstream ecosystems. From this point of view, it is essential to consider all actions to reduce and control water withdrawal. Reducing water losses in the domestic distribution to 20% will reduce the withdrawal to half. The domestic use weight will reduce to 5.8%, and the water balance will be in equilibrium.

Another aspect that can indicate a system weakness effect is climate change. Reduced recharge related to less rainfall and increased temperature will affect the spring's flow and consequently impact the environment and agriculture. This situation has occurred in different areas, and several authors have studied it. For example, in Marocco, a country in North Africa (Kherbache et al., 2023), a decrease in river flow of 41% has been recorded from 1971-1980 to 2009-2017. It has been attributed to climate change, recurring drought and deficit in rainfall, an average annual temperature increase, and withdrawal from dams and aquifers.

Thus, building tools to prevent and manage these critical conditions becomes essential. This objective will be accomplished by building a simplified water balance model over the watershed and using a simplified database of meteorological data obtained from stations in the plain with an extended dataset across the years.

Water balance model implementation

A series of adjustments are introduced to use the meteorological data in the simplified model for the water balance. The available data on rainfall and annual temperature over a long period are given at the bottom of the structure at an average altitude of 30 m, corresponding to the reference weather station of Doganella di Ninfa. Therefore, average temperatures have been corrected, considering the average elevation of 612 m (orthometric height). The data from 2005 to 2007 on 12 stations around the watershed was collected to evaluate the local thermal gradient (Fig. 9a), and the relation between altitude and the annual mean temperature was plotted. Figure 9b reports the regression in the data, showing a thermal gradient of -5.6 °C/km with a negligible drift of 0.01 °C.

A correlation has been developed to evaluate the rainfall in the watershed using the data obtained in "Progetto Monti Lepini" (Alimonti et al., 2011). This work used distributed water balance and geostatistics methodologies, allowing a detailed system description over five years of observation. Thus, Figure 10 reports a correlation between the rainfall data on a yearly base from a single station and the rainfall obtained with the distributed model over the entire watershed. The correlation shows that rainfall over the watershed is about 25% larger than those measured in the plain weather station, with a high regression coefficient of 0.975.

After calculating the effective rainfall, the water balance model will estimate the infiltration via the CIP. The

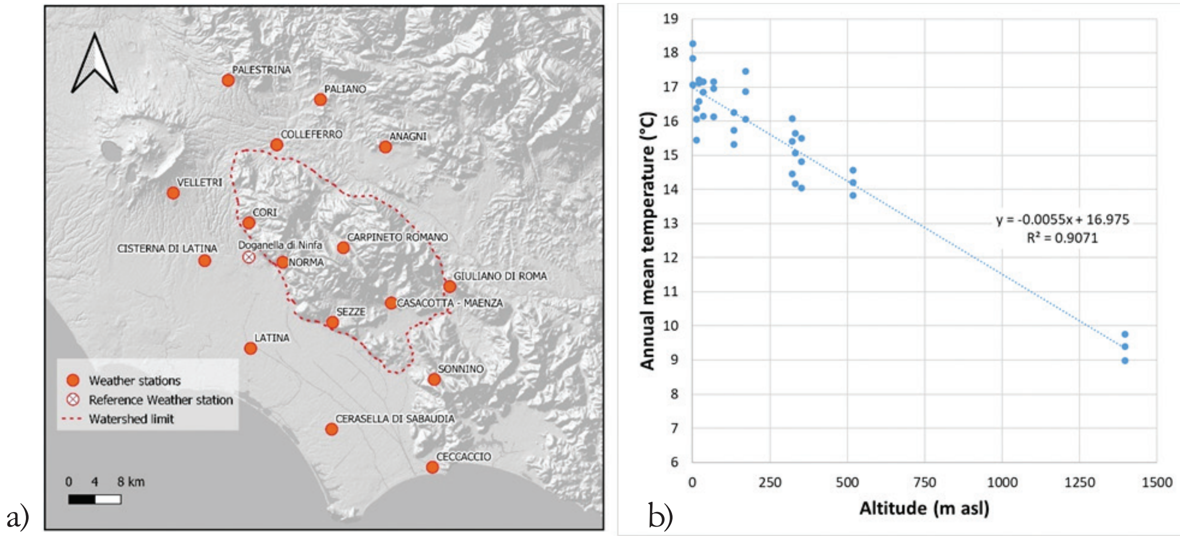

Fig. 9 - Correlation between altitude and annual mean temperature for weather stations around and over the Mt. Lepini structure. a) Weather station map b) Correlation plot.

Fig. 9 - Correlazione tra l'altitudine e la temperature media annuael per le stazioni meteo sopra e intorno ai Monti Lepini a) mappa delle stazioni meteo b) correlazione.

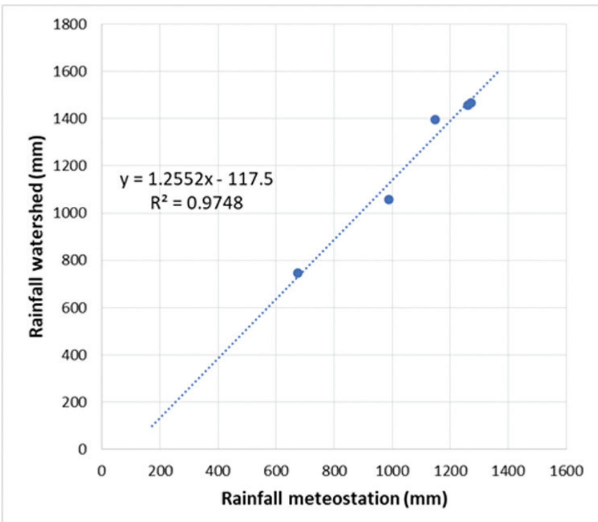

Fig. 10 - Regression between rainfalls measured at lowland weather stations and estimated rainfalls over the watershed with geostatistics in "Progetto Monti Lepini.

Fig. 10 - Regressione tra precipitazioni misurate nelle stazioni meteorologiche di pianura e precipitazioni stimate sul bacino idrografico con geostatistiche nel "Progetto Monti Lepini"

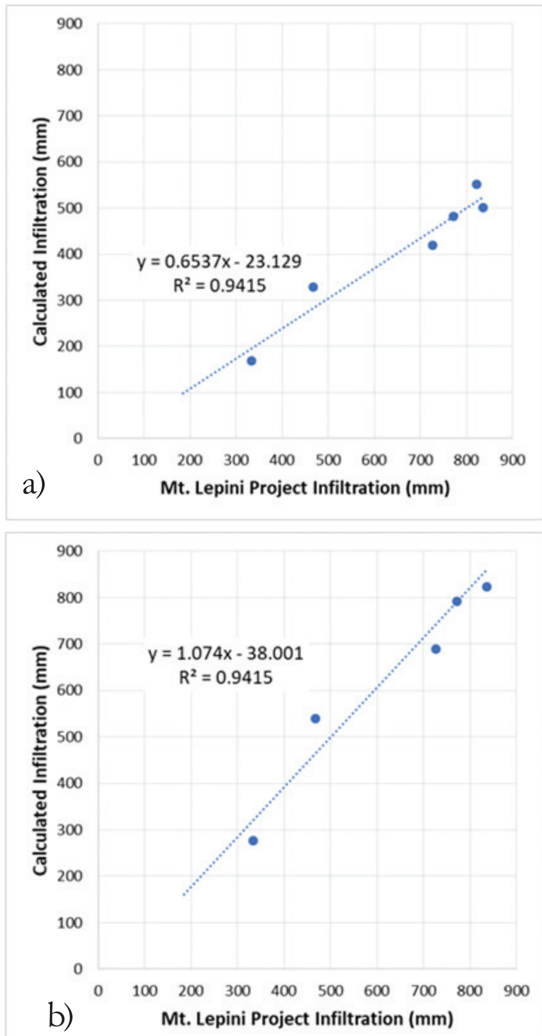

Fig. 11 - Comparison of infiltration and tuning of the CIP. a) original CIP, 49.3% b) tuned CIP, 81%.

Fig. 11 - Confronto tra infiltrazione e CIP (a) originale CIP=49,3%, (b) accordato CIP=81%.

availability of infiltration data from the "Progetto Monti Lepini" allows us to compare it with values calculated with the CIP model previously presented. Figure 11 shows those data and the optimized results by regression over data. The value of the CIP under regression is 81%, showing a different result from the calculated value of 49.3%. This regressed value reduces the underestimation of infiltration over the watershed. The CIP close to 1 confirms the hypothesis that all the net rainfall feeds the aquifer. The high CIP is also related to endorheic areas that are not considered in the CIP model.

A back analysis of the inaccuracy of the CIP estimation shows the limit of the adopted method. The first issue is the evaluation of the geological CIP that is lower than the tuned value (75.8% vs. 81%). The primary consideration is that the values adopted in the calculations are too low and do not consider the presence of endorheic areas. The second issue is the low value obtained for the CIPps. The method presented by Brugioni et al. (2008) has too few intervals in the discretization, reducing the possibility of a continuous variation of the CIP. The predominant land use in the specific case study is cultivated land, with 50,7%. The rest is predominantly prairies and forests. Those considerations introduced another aspect: the dataset used in defining the land use and the categories used. The land use categories can reduce the value obtained a lot. In the present case study, the difference appears to be too significant. In conclusion, the Brugioni method for CIP calculation is preferred in near-flat regions with various coverage. In the case of mountains, high permeable formation can give an underestimated infiltration value.

Analysis of Mt. Lepini aquifer recharge

The distribution of the recharge over the Mt. Lepini system is obtained by applying the tuned model to the historical series of 95 years (1924-2020) of meteorological data. The distribution is lognormal, with a mean of 336.4 Mm^3 and a standard deviation of 122.7 Mm^3. The mean value is slightly less than the obtained value from Table 8 but within the range of 95% of the population.

Figure 12 reports the histogram of the recharge data and the corresponding cumulated probability curve. This probability curve can be used to evaluate the reliability of the rechange of the Mt. Lepini aquifer.

Referring to the water balance in Table 8, assuming the total water discharge is 427 Mm^3, the probability of having the annual recharge less than the discharge is 80%. These considerations define the recharge failure rate. The value is very high and highlights the possibility of a water crisis and changes in the stored water inside the aquifer. Comparing the water balance of Mt. Lepini and the water balance of the volcanic aquifers of Latium, Mazza et al. (2014) define the Mt. Lepini hydrogeological system as less stressed than the volcanic one where the budget imbalances cannot be attributed only to a few isolated cases but rather is a general phenomenon. In the volcanic sector, the groundwater withdrawal exceeds 45% of the total recharge, while in the Mt. Lepini is about 20 % (Mazza et al., 2014). On the contrary, it appears to be very vulnerable to changes in recharge.

Historical data has been analyzed to highlight this vulnerability. Figure 13 reports the recharge calculated over the historical data range. The limitations of this approach are the assumption of constant model parameters over time and the effect of groundwater storage changes. The first one is resumed in the infiltration coefficient CIP. The land use and anthropic pressure over the water resource have changed, inducing a possible change in the CIP. The groundwater storage can be considered negligible over long periods (e.g. 20-30 years). For short periods like 2005-2010 should be considered.

Figure 13 reports the values of the recharge of Mt. Lepini between 1924 and 2020. This type of representation highlights the maximum and minimum values and the average and median values, showing the data distribution within the interval. The analysis of the results allows us to extrapolate the changes in the system, probably due to the evolution of land use and coverage. The trend is likely the rainfall trend with the observed changes.

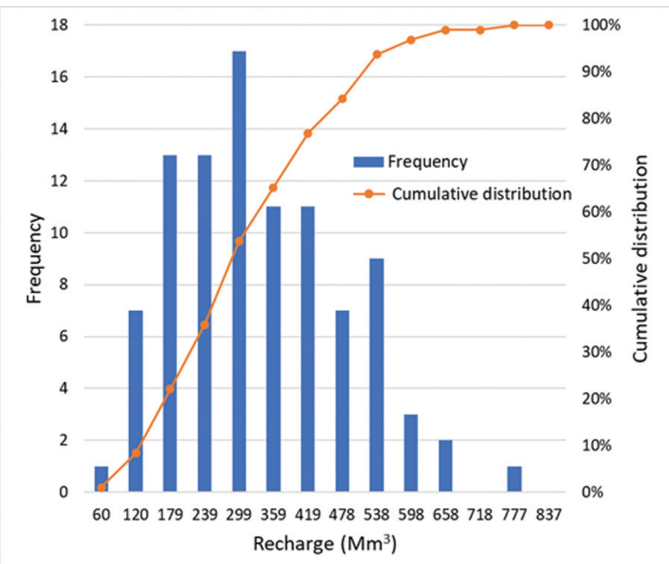

Fig. 12 - Histogram and cumulated distribution curve of the recharge over the Mt. Lepini system for the 95 years (1924-2020) of meteorological data.

Fig. 12 - Istogramma e curva della distribuzione cumulata della ricarica sul Sistema dei Monti Lepini per 95 anni (1924-2020) dei dati meteorologici.

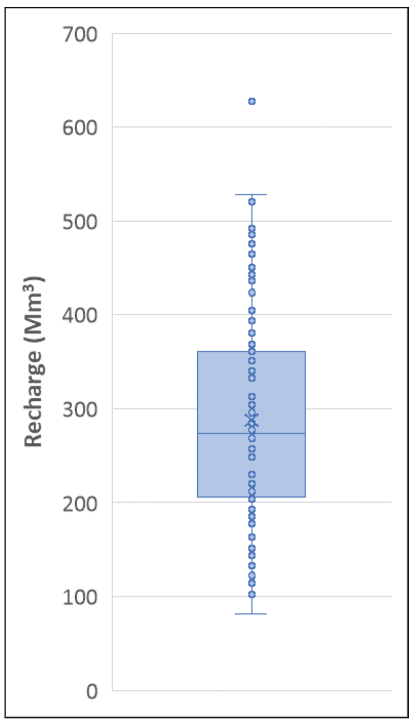

Fig. 13 - Recharge of Mt. Lepini over the period 1924-2020.

Fig. 13 - Ricarica dei Monti Lepini nel periodo 1924-2020.

Considering the definition of the vulnerability and reliability indexes of water resources systems, the total water discharge of 427 Mm^3 per year accounts for a vulnerability of the water system of 77.9% and a reliability of 22.1%. The sustainability index is 21.5%, a meagre value. Those values classify this water system as vulnerable and unreliable.

After this analysis, a question may arise. Critical drought conditions have rarely been observed. An arid period occurred in the 1940s, a situation documented especially for the Ninfa Spring, located at the highest altitude, where the lake level dropped significantly. Similar situations occurred in the 1990s, most recently in 2017. The other spring systems are located at lower altitudes and, therefore, are less likely to be affected by drought crises. In any case, the flow rate has dropped in all spring systems.

Concerning the studies mentioned above (IPCC, 2024; Copernicus, 2024), it is vital to consider the possible alteration of the system considering climate change and the expected variation in terms of temperature and precipitation. The increase in the annual mean temperature, connected to global warming, will produce an increase in the evapotranspiration component and the reduction of the infiltration and, thus, the recharge. An increase in temperature alone does not significantly affect the system's reliability. With an increase in temperature and a decrease in rainfall, the system's reliability decreases significantly (Rizzoli, 2024).

Considering the recharge depletion and the increasing anthropic water demand, the reduction of spring discharge and stream base flow is expected, and the risk of a water crisis and drought events increases. Consequently, the water demand will be highly affected, and the water supply must be managed considering all ecosystem services produced by the water resource.

Conclusions

The present work presents a methodology to evaluate water resource assessment in a watershed using a simplified water balance method. The methodology uses available data from weather stations and the historical analysis of temperatures and precipitations over 95 years. The limited availability of weather stations at altitudes gives us the target to use the plain weather station data and extend that data over the entire watershed. This goal is obtained using the "Progetto Monti Lepini" results based on a distributed water balance model and geostatistics methodologies.

The Mt. Lepini aquifer between 2005 and 2010 shows a system nearly balanced, with a small underbalance (7.5%). The most important aspect is the base flow, which constitutes 77% of the total discharge. The ecosystem and its services, as well as the environmental sustainability of the biosphere, are strictly related to the base flow. The observed change in time of the base flow is due to the exploitation of water resources from the plain, which has become a threat. The water balance model was applied to the 95-year historical data set with a significant assumption that there would be no change in land use parameters across time. The analysis of the system's reliability to the recharge highlights a high-risk condition with a vulnerability of 78% and a sustainability index of 22%.

The results highlight a critical situation for a water system like Mt. Lepini, where the discharge is directly connected to the recharge with a rate of failure of 80%, considering the average mean discharge of 427 Mm^3/y. This critical situation is a straightforward consequence of the carbonatic nature of the hosting rocks and the system's fracture-dominant permeability. The management of this water system should consider all the ecosystem services exerted by the water resource. Those are the water supply to human activities and the existing water ecosystems downstream of the spring systems.

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Author contributions

This manuscript is the result of a collaborative research effort, in which each author provided a substantial and distinct contribution. The synergy between their diverse expertise allowed for a rigorous and in-depth exploration of the complex topic. Specifically:

Claudio Alimonti made a decisive contribution to the definition of the methodology, the execution of the formal analysis, the drafting of the original manuscript, and the management of the data, overseeing its acquisition and organization.

Massimo Amodio played a key role in the supervision of the entire project, providing the foundational conceptualization and guiding the definition of the methodology, as well as actively participating in the drafting of the original manuscript.

Angelica Rizzoli provided an essential contribution to the drafting of the original manuscript, the formal analysis of the data, and its curation, ensuring the accuracy and consistency of the information presented.

All authors have read and agreed to the published version of the manuscript.

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